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VOL II

IN SITU SOIL VENTING - FULL SCALE TEST HILL AFB, GUIDANCE DOCUMENT

D. W. DEPAOLI, S. E. HERBES, J. H. WILSON, D. K. SOLOMON, AND H. L. JENNINGS

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The purpose of this project was to demonstrate a full-scale in situ soil venting technology and to carefully document the design, operation and performance of this system so that it could be applied at other Air Force contaminated sites. Although this technology is now commercially available, its ability to fully remediate jet fuel spills had never been proven, nor had the full-scale costs ever been validated when catalytic incineration is used as an emission control method. ESL Technical Report 90-21 is in three volumes. The first volume is a complete literature review of previous soil venting research and field work. Volume II is a guidance manual which provides important design information and describes methods of pilot testing this technology prior to full-scale application. Results of the Hill AFB test are included in Volume III. These publications will provide invaluable information to Air Force engineers responsible for cleaning up chemically contaminated sites.

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EXECUTIVE SUMMARY

A. OBJECTIVE

This document is intended for use by U.S. Air Force engineers, decision-makers, and their contractors in the application of *in situ* soil venting (ISSV) for remediation of spills of volatile organic compounds. The information provided in this manual will be useful for guidance in site characterization, technology selection, design, and operation of a soil venting system.

B. BACKGROUND

In situ soil venting, also commonly referred to as soil vapor extraction, is a rapidly growing technology for the removal of volatile contaminant spills in unsaturated zone soils. In this technique, the soil is decontaminated in place by pulling air through the soil, vaporizing and removing the contaminants.

The technique first appeared in the literature in 1982. Since that time a few well-documented field studies have demonstrated potential for effective treatment in certain situations, and several vendors have claimed success in site remediations. To this point, however, little detailed information has been published regarding the design and implementation of soil venting systems.

This manual provides potential users of the technology with a compilation of the pertinent information appearing in the literature with analyses and techniques developed during the Hill AFB soil venting field demonstration.

C. SCOPE

This document provides information on each aspect of implementation of soil venting. An introduction to the technology, including a general description and applicability guidelines, is presented. Additional information appearing in the literature is presented in ESL TR 90-21 Volume I, *In Situ* Soil Venting: A Review of the Literature. The technology selection process is discussed, listing the information necessary to make a good decision about the feasibility of soil venting, and describing the means to collect this information. The steps of conceptual design, pilot testing and full-scale design, operation, and shutdown are detailed. An economic model is presented for comparison of cost for different design approaches.

D. METHODOLOGY

This document was prepared using the experience gained during conduction of the Hill AFB soil venting field demonstration. Useful information appearing in the literature was combined with analyses and practical experience gained during the demonstration to produce this manual.

E. TEST DESCRIPTION

The Hill AFB soil venting field demonstration is described in full in ESL TR 90-21 Volume III, Field Demonstration of *In Situ* Soil Venting at Hill Air Force Base JP-4 Jet Fuel Spill Site. Examples using data from the demonstration are included in this manual for illustration.

F. RESULTS

It is imperative that reliable and complete site characterization data are obtained. Data of particular interest in the selection and design of soil venting include the composition and concentration of contaminants, depth and areal distribution of contaminants, soil stratigraphy, soil moisture content, depth to groundwater, and air permeability of the soil. Of these, the single most important design variable is air permeability of the soil, which is frequently not measured in site characterizations. Section III.C. of this manual describes simple *in situ* tests which can be conducted to provide rapid, inexpensive, and accurate measurements of air permeability.

The selection of soil venting or any other remediation technology must be based upon technical, economic, and political issues. Technical issues to be considered in the suitability of soil venting include contaminant volatility, air permeability of the soil, size and depth of spill with respect to capabilities of excavation, and complexity of soil stratigraphy and geohydrology. Other issues to be considered are cost and legal implications, including patent issues and regulatory requirements. A conceptual design as developed in Section IV and Appendix C may be used in conjunction with the econometric model presented in Section VII and Appendices F and G to provide cost estimates for comparison with other potential treatment processes.

A pilot test should be conducted prior to full-scale design and implementation. Data to be obtained during the pilot test will include air permeability estimates and contaminant removal rates. It is recommended that the pilot test be operated long enough that gas concentrations are significantly lowered and a shutdown and restart be conducted to estimate the importance of diffusion control upon contaminant removal.

In most cases, the information from the site characterization and pilot test will be used to design a full-scale system using approximate methods which have their basis in radial flow and equilibrium removal assumptions. However, advances are being made in modelling of coupled air flow and contaminant transport which will be useful in system design and optimization. When applying such models, one must recognize the limitations imposed both by the assumptions made by the transport equations in the model and the uncertainty in the inputs to the model.

Full-scale system design defines the number, placement, and construction of vents, the type and layout of piping, size and design of vapor/liquid separator, vacuum and flow capacity of a given type of blower, and emissions control type and size. Other equipment necessary are safety equipment such as flame arrestors and explosive gas detectors, pressure/vacuum gauges, flowmeters, and vapor analyzers.

In general, well-designed soil venting systems may be operated with limited long-term manpower requirements. A system should be operated with the general strategy to continually maximize the extracted gas contaminant concentration. Such a strategy involves periodic adjustment of operating conditions, thus will require a certain degree of attention and documentation of system operation history. Shutdown of soil venting operations is contingent upon meeting regulatory requirements; it is important to have shutdown criteria defined in advance.

G. CONCLUSIONS

In situ soil venting is an effective and potentially cost-effective technique which should be considered for the remediation of volatile contaminant spills. However, due to limited documented field work, the uncertainty involved in and lack of development of predictive models, and the site-specific nature of the technique, an explicit design procedure cannot be defined. This manual discusses each aspect of implementation to provide guidance in selecting and applying the technology.

Application of soil venting carries with it the uncertainties that are present in any environmental remediation, particularly *in situ* techniques. These uncertainties will impact scheduling, design, cost, and technology selection. Some of the uncertainties to consider include:

1. The amount of contaminant present at the site will not be known precisely due to soil and contaminant distribution heterogeneities. The impact of this point is that precise scheduling and budgeting will be impossible and assessment of progress toward a cleanup goal will be difficult.
2. Heterogeneities in the soil and contaminant distribution and possible multiple factors controlling removal make projection of removal via modelling an uncertain venture.
3. The *in situ* nature of the technology leads to the possibility of remaining patches of contamination in a seemingly otherwise treated site.

H. RECOMMENDATIONS

It is recommended that ISSV be considered for remediation of volatile contaminant spills. ISSV is still a relatively new remediation technology with great room for improvements and additions to our knowledge through study of field applications. Listed below are major points in which improvements would benefit users of this technology:

1. A major point of doubt and controversy surrounding ISSV is the applicability of cleanup standards. The technique is undoubtedly one of the most effective means of remediation, yet regulatory standards based on statistical soil sampling with low compound-specific limits makes application of this or any other *in situ* technique less attractive.
2. ISSV is still an unfamiliar technology to many regulators and potential users. The publication of the technical details of successful applications of this technology will be useful in informing the public of its potential and will provide a larger information base suitable for increased regulatory approval.
3. Improved models will be useful for better budgeting and scheduling of venting applications. Continued work needs to be performed in the laboratory to determine factors controlling removal under different soil, contaminant, and flow conditions, and in documented field applications from which data may be obtained for validation of models.
4. Improvements in cost-effectiveness of the technology may be foreseen by increasing removal rates through such methods as heat enhancement and by optimizing biodegradation during venting operations. Continued further testing of these and other enhancements of venting is urged.

PREFACE

This document was prepared by the Oak Ridge National Laboratory, P. O. Box 2008, Oak Ridge, TN 37831-6044, for the Air Force Engineering and Services Center, Engineering and Services Laboratory, Tyndall Air Force Base, Florida, as a partial means of fulfillment of the statement of work entitled "*In Situ* Soil Venting" in accordance with DOE Interagency Agreement No. 1489-1489 A1. The period of performance of this work was from April 1987 to January 1990. Oak Ridge National Laboratory is managed by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy under contract DE-AC05-84OR214000.

This document details the results of activities performed under Task 4.4 of the statement of work, Phase 4 - Final Report. Related documents completed under the same contract are ESL TR 90-21 Volume I, *In Situ* Soil Venting: A Review of the Literature, and ESL TR 90-21 Volume III, Field Demonstration of *In Situ* Soil Venting at Hill Air Force Base JP-4 Jet Fuel Spill Site. The AFESC/RDVW Project Officers for this effort were Capt. Edward Heyse, Capt. Michael Elliott, Mr. Doug Downey, and Capt. Edward Marchand.

Mention of trade names or commercial products within this document does not constitute endorsement or recommendation for use.

Constructive system design guidance was obtained from our consultants, Mr. James Malot of Terra Vac, Inc., and Ms. Nancy Metzer and Dr. Michael Corbin of R. F. Weston, Inc.

We would like to thank Dr. Neil Hutzler of Michigan Technological University for several interesting discussions regarding soil venting and for his constructive editing of these reports.

This report has been reviewed by the Public Affairs office and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

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LIST OF ABBREVIATIONS

AFB	Air Force Base
ASCII	American Standard Code for Information Interchange
BLS	Below Land Surface
BTX	Benzene, Toluene, and Xylene
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
DOE	Department of Energy
FAR	Federal Acquisition Regulation
FEMAIR	Finite-Element Model for Air Transport
FID	Flame Ionization Detector
FTE	Full-Time Equivalent
FY	Fiscal Year
GAO	General Accounting Office
GC	Gas Chromatography
GC-MS	Gas Chromatography - Mass Spectrometry
HQ AFESC	Head Quarters Air Force Engineering Services Center
HQ MSD/JAN	Head Quarters Munitions Systems Division (JAN is mailing code)
IRP	Air Force Installation Restoration Program
ISSV	*In Situ* Soil Venting
LEL	Lower Explosion Limit
NEMA	National Electrical Manufacturers' Association
NEPA	National Fire Protection Association
PC	Personal Computer
PCE	Perchloroethylene (Tetrachloroethylene)
PID	Photoionization Detector
PPMV	Parts Per Million-Volume Basis
PVC	Polyvinyl Chloride
QA	Quality Assurance
QC	Quality Control
RCRA	Resource Conservation and Recovery Act

LIST OF ABBREVIATIONS
(CONCLUDED)

RDVW	Mailing Code
RF	Radio Frequency
SARA	Superfund Amendments and Reauthorization Act
TCE	Trichloroethylene
TEFC	Totally Enclosed, Fan Cooled
TSCA	Toxic Substances Control Act
USEPA, EPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VOC	Volatile Organic Compound

LIST OF SYMBOLS*

A	Area of contaminated soil zone (L^2)
AFF	Derived air flow rate (L^3/t)
b	Length of *in situ* permeability test interval (L)
CAP	Size of carbon adsorption unit (M)
C_{av}	Average contaminant concentration in soil (M/L^3)
C_i	Liquid concentration of component i (mole/L^3)
C_1	Initial gas concentration (mole/L^3)
C_2	Gas concentration at system restart (mole/L^3)
D	Depth of horizontal vent (L)
DP	Difference in pressure between atmosphere and vent (M/Lt^2)
Eff	Venting efficiency (dimensionless)
g	Gravitational constant (L/t^2)
GAC	Amount of carbon regenerated per year (M)
h	Length of slotted sector of vent (L)
H	Henry's law coefficient, dimensionless (mole/L^3 gas) / (mole/m^3 liquid)
INT	Annual applied interest rate (fraction)
k	Air permeability (L^2)
k_r	Relative permeability (dimensionless)
k_{ij}	Intrinsic permeability tensor (L^2)
K_{ij}	Hydraulic conductivity (L/t)
L	Length of slotted sector of horizontal vent (L)
m	Molecular weight (M/mole)
M	Estimated spill mass (M)
N	Number of extraction vents (dimensionless)
N_i	Number of moles of component i (dimensionless)
N_T	Total number of moles (dimensionless)
p	Pressure (M/Lt^2)
P	Pressure (M/Lt^2)
PC	Pressure correction term (dimensionless)
P_{atm}	Atmospheric pressure (M/Lt^2)

LIST OF SYMBOLS
(CONTINUED)

P_{av}	Volume overage pressure within the radius of influence (M/Lt^2)
P_i	Partial pressure of component i (M/Lt^2)
P_i^{sat}	Vapor pressure of component i (M/Lt^2)
P_P	Pressure at monitoring point (M/Lt^2)
P_v	Pressure in extraction vent (M/Lt^2)
q	Single vent volumetric flow rate (L^3/t)
qi	Air velocity or flux (L/t or L^3/L^2t)
Q	Total volumetric flow rate (L^3/t)
QINT	Derived quarterly interest rate (fraction)
Q_m	Mass flow rate (M/t)
r	Radius (L)
r_{atm}	Minimum radial distance from center of vent to the point where the pressure is essentially atmospheric (L)
r_i	Radius of influence, $\leq r_{atm}$ (L)
r_f	Borehole radius factor (dimensionless)
r_v	Radius of vent (L)
r_{well}	Borehole radius (L)
R	Universal gas constant (ML^2/mole Tt^2)
RF	Removal factor (L^3 gas/M spill)
RF_{adj}	Adjusted removal factor (L^3 gas/M spill)
t	Time (t)
T	Absolute temperature (T)
V	Volume (L^3)
V_{tot}	Estimate of required gas volume (L^3)
W	Width of contaminated soil volume having length, L and depth, D (L)
$W(u)_{ss}$	Permeability test parameter (dimensionless)
x_i	Liquid phase mole fraction of component i (dimensionless)
X	Cumulative air flow per weight of initial spill (L^3/M)
X_i	Spatial coordinate (L)

LIST OF SYMBOLS
(CONCLUDED)

y_i	Vapor phase mole fraction of component i (dimensionless)
Y	Current air stream VOC concentration (M/L^3)
Y_i	Vapor concentration of component i ($mole/L^3$)

Greek Symbols

Δp	Pressure change (M/Lt^2)
Δt	Elapsed time (t)
μ	Dynamic viscosity (M/Lt)
ρ	Density (M/L^3)
θ	Total porosity (dimensionless)
θ_r	Residual volumetric moisture content (dimensionless)
θ_w	Volumetric soil moisture content (dimensionless)
λ	Pore size distribution index (dimensionless)

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*Dimensions are given in terms of mass (M), length (L), time (t), and temperature (T).

GUIDANCE MANUAL FOR THE APPLICATION OF *IN SITU* SOIL VENTING FOR THE REMEDIATION OF SOILS CONTAMINATED WITH VOLATILE ORGANIC COMPOUNDS

SECTION I

INTRODUCTION

A. OBJECTIVE

This document is intended for use by U.S. Air Force engineers, decision-makers, and their contractors in the application of *in situ* soil venting (ISSV) for remediation of spills of volatile organic compounds. The information provided in this report will be useful for guidance in site characterization, technology selection, design, and operation of a soil-venting application.

Soil venting system design depends on many factors which will vary greatly from site to site, and the current lack of universal understanding of the many contributing processes does not allow a simple design manual to be prepared at this time. This document, as its title indicates, will provide guidance by presenting concepts which must be considered in the application of the technology. The specifics included in this document are for application to JP-4 jet-fuel spills; however, the concepts are applicable to other volatile compounds or mixtures when proper consideration is given to the contaminant properties.

The few design equations presented are the result of assumptions and over-simplification. They should, therefore, be used only as a starting point for detailed consideration of a venting application. One must also consider the uncertainties that will exist for any technology applied in a field setting. Engineering judgment and previous experience with this technology must be applied beyond the guidance provided in this manual for a successful application of soil venting.

B. BACKGROUND

1. How Soil Venting Works

In situ soil venting, also referred to as *in situ* volatilization, *in situ* air stripping, or soil vapor extraction, is a promising technology for removal of volatile contaminant spills in unsaturated zone soils. A conceptual picture of ISSV is shown in Figure 1. In this technique, the soil is decontaminated in place by pulling air through the soil. Air removed from the soil by an extraction vent and vacuum blower may be resupplied passively via infiltration from the surface, or through injection vents—either passively or by pumping. The air flow sweeps out the soil gas, disrupting the equilibrium existing between hydrocarbons that are (1) sorbed on the soil, (2) dissolved in soil-pore water, (3) present in a separate hydrocarbon phase, and (4) present as vapor. This air flow causes

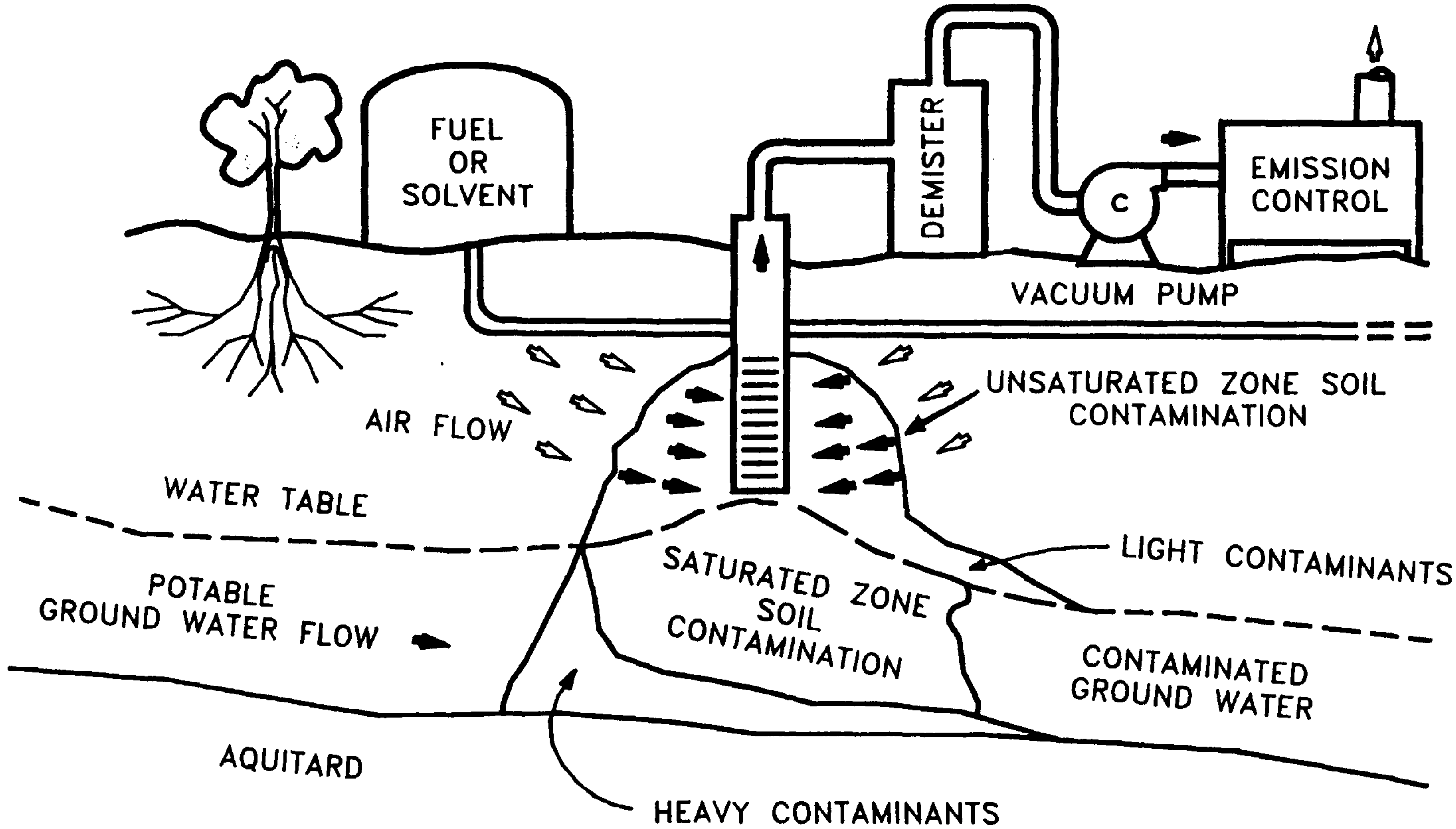


Figure 1. *In Situ* Soil Venting.

volatilization and subsequent removal of the contaminants in the air stream. Depending upon the flow rate, contaminant type and concentration, as well as local environmental regulations, the extracted gas stream may be discharged directly to the atmosphere or sent to an emissions-control device.

ISSV has proven to be a cost-effective decontamination technology. It is extremely useful in decontaminating unsaturated zone soils, both in preventing explosive hazards caused by subsurface fuel vapor and in removing contaminants before they reach the groundwater. Soil venting may also be used in conjunction with pump-and-treat groundwater remediation techniques for complete cleanup of a site where the hydrocarbons have reached the water table.

2. General Applicability of the Technology

In situ soil venting is generally applicable to spills of volatile organic compounds (VOCs) in highly permeable soils, although it has been reported to be successful in less permeable soils. ISSV is most applicable to a spill site where contamination may migrate to the groundwater in the future; however, it may also be used in conjunction with pump-and-treat techniques for faster remediation of unsaturated and saturated zone contamination.

The application and performance of soil venting is site-specific. Variables to be considered include (1) the size of the spill, (2) the type of contaminant, and (3) the geohydrological factors. In general, larger and/or deeper contaminated soil zones favor soil venting over excavation; although a size criterion may be waived when considering treatment of a site containing a building or other valuable structure. ISSV is less easily applied to soils with complex stratification or low permeability, although recent field tests have demonstrated successful removal in lower permeability soils (References 8 and 15).

Various design strategies of soil venting have been implemented, each exhibiting promising results. The simplest design includes only vapor-extraction vents, which may be adequate for remediation at many sites. For deep contamination, or for cases with free product on the water table, passive inlet vents may be included to direct air flow into the lower soil areas. Other systems include pressurized injection vents around the contamination area to increase flow rate and control. An impermeable surface barrier is frequently recommended in most cases to prevent rainwater infiltration and short-circuit of the air flow from the surface. Several different types of blowers have been used; selection depends on site-specific factors such as spill size and soil permeability. Specific site characterization data should be collected and a pilot system should be operated at the spill site to determine design parameters.

It may be difficult to predict the overall effectiveness of ISSV or any other *in situ* restoration technique, since heterogeneity of soil structure and contamination location preclude measuring the initial mass present at a site. Factors affecting the rate at which chemicals can be removed by ISSV include (1) amount and geometry of air flow, (2) nature of the contaminants, (3) geohydrology, (4) temperature, (5) moisture, and (6) aerobic bioactivity. In general, factors which increase contaminant removal rates are higher air flow through contaminated soil zones, contaminants of higher volatility, soils of simple stratification with high air permeability, higher temperatures, lower moisture content, and higher aerobic activity.

ISSV has proven to be a cost-effective remediation technology. Field implementations have demonstrated removal of gasoline and chlorinated solvents, including trichloroethylene (TCE), perchloroethylene (PCE) and carbon tetrachloride, from spill sites with minimal disruption of normal activities in the area. The accompanying literature review, Volume I, discusses these results in detail. In addition, the Air Force Engineering Services Center has recently completed a demonstration of ISSV at a JP-4 jet-fuel spill site. This guidance manual is based, in part, on the experience gained from this successful demonstration.

C. SCOPE

The document begins with an introduction to the technology (Section I), which includes a description and listing of general applicability guidelines. Section II, which covers the technology selection process, lists the site information necessary to make a good decision about the feasibility of a venting application, describes technical and other factors important to the decision, and briefly describes other alternatives to venting. Section III outlines the means for collection of the necessary site information. Section IV provides an algorithm for conceptual design of a system for use in comparing technologies and providing a basis for further design modifications. Section V describes pilot testing. Section VI steps through the implementation of the technology, including design, strategies of operation, and shutdown. Section VII presents a spreadsheet-based economic model which may be used to compare the cost-effectiveness of different design approaches.

SECTION II

TECHNOLOGY SELECTION

The initial decision of which remediation technology to implement is, in some respects, more complicated and difficult than the design, construction, and operation of the system. To be performed accurately, this decision process requires much site-specific information and may have several decision points. This section will outline the decision process and describe the information needed to evaluate soil venting as a remediation option. This document will provide guidance for evaluating soil venting in the decision process, but will not propose criteria for selection of particular technologies.

A flowsheet of the decision process specific to ISSV is shown in Figure 2. This flowsheet is similar to that presented by Johnson, et al. (Reference 1). This particular document and others referenced in this section may provide further insight into the decision-making process.

The first step in the decision process is the collection of site-specific information necessary for assessing general site suitability both technically and conceptually. Section II.A. outlines criteria for determining the general applicability of ISSV and Section III outlines the tests necessary to provide relevant information.

If ISSV appears technically feasible, other factors, such as cost, regulatory requirements, and political and legal implications, must be considered. Section II.B. discusses several of these factors.

If ISSV appears both technically and politically attractive, a conceptual design should be prepared. Section IV discusses the elements of a conceptual design and techniques for rough estimation of the cost and time for site cleanup. Further information on these subjects may be found in References 1 and 2.

The conceptual design must be evaluated against other remediation alternatives. Section II.C discusses other treatment options. Because each case will be evaluated with different weightings for cost, time for treatment, possibility for incomplete remediation, and so on, this document will not attempt to provide guidance toward the actual decision. However, several studies (e.g., References 3, 4, 5, and 6) have provided comparisons of treatment technologies that may be helpful in the decision.

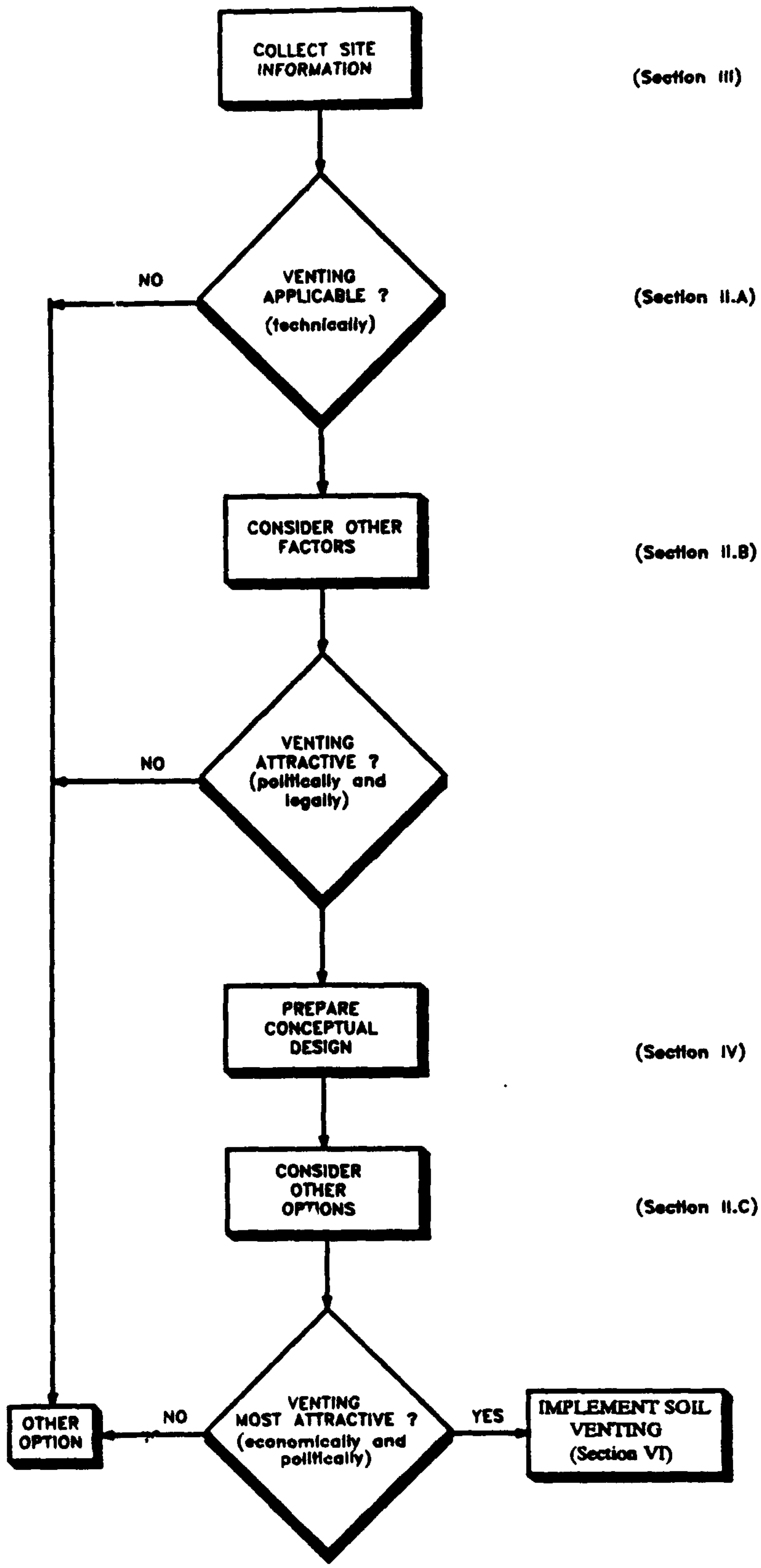


Figure 2. Technology Selection Process.

A. TECHNICAL FACTORS AFFECTING FEASIBILITY OF SOIL VENTING

1. Spill Characteristics

Characteristics of spilled liquid contaminants are important in evaluating the appropriateness of ISSV as a remediation option. These include the spill size, volatility, density, and composition (single constituent vs. mixture).

a. Spill Size

ISSV becomes an attractive treatment alternative from the standpoint of cost, relative to that of excavation, at a contamination zone size of about 500 cubic yards, or at depths of greater than 10 feet (Reference 7). ISSV is applicable at much greater depths and, for spill depths of greater than 40 feet, the cost advantage over excavation is substantial (Reference 9).

b. Volatility

The effectiveness of ISSV for removal of VOCs depends primarily on the vapor pressure of the spill constituents. No rigorous guidelines have been developed for identifying applicable compounds, but a general guideline (Reference 8) states that ISSV is effective for compounds having a vapor pressure of 0.5 to 1.0 mm Hg (20°C) or greater. Table 1 shows the vapor pressure of several common soil contaminants at 20°C.

A second criterion is the extent to which spill constituents partition between air and water. Highly soluble compounds, even though highly volatile, will preferentially dissolve in soil moisture and are removed less rapidly in vented air. Air-to-water partitioning is described by the Henry's Law coefficient (H), which may be expressed in several different units. Compounds with dimensionless H values greater than 0.01 (as: mole/m^3-gas/moles/m^3-liquid) are likely to be adequately removed by ISSV (Reference 9). Table 1 shows the dimensionless Henry's coefficients for several common soil contaminants at 20°C.

A third factor affecting contaminant removal is sorption to soil particles. Generally, more polar compounds (including many pesticides) and contaminants composed of larger molecules (polychlorinated biphenyls, polycyclic aromatic hydrocarbons, and hydrocarbons containing greater than 16 carbon atoms) are less volatile and more readily sorbed by soil. Removal of these compounds by ISSV is impractical because of the very small proportion of the compound present in the soil vapor phase.

TABLE 1. LIST OF COMMON SOIL CONTAMINANTS

COMPOUND	VAPOR[a] PRESSURE (mm Hg)	HENRY'S[b] COEFFICIENT (mole/m^3 / mole/m^3)
Vinyl Chloride	2299.4	0.87
Dichloromethane	353.3	0.09
Acetone	183.6	
Chloroform	193.4	0.17
n-Hexane	120.4	26.53
1,1,1-Trichloroethane	100.0[c]	0.59
Carbon Tetrachloride	90.5	0.98
Cyclohexane	77.0	6.16
Benzene	74.7	0.19
Trichloroethene	58.1	0.35
n-Heptane	35.3	
Toluene	21.7	0.23
1,1,2-Trichloroethane	18.2	0.03
Tetrachloroethene	13.9	0.59
n-Octane	10.4	
Chlorobenzene	8.9	0.14
Ethylbenzene	7.0	0.25
p-Xylene	6.5	0.26
m-Xylene	5.4	0.25
o-Xylene	4.8	0.18
n-Decane	0.9	
Naphthalene	0.2	
1,1-Dichloroethene		0.86
trans-1,2-Dichloroethene		0.35
cis-1,2-Dichloroethene		0.16
1,3-Dichlorobenzene		0.12
1,4-Dichlorobenzene		0.11
1,2-Dichlorobenzene		0.07
Ethylene dibromide		0.02
1,1,2,2-Tetrachloroethane		0.02

[a]Vapor pressure was determined at 20°C from Reference 10.
[b]Henry's coefficients were determined at 20°C from Reference 11.
[c]Reference 12.

c. Density

Volatile liquids that are both immiscible with and lighter than water, such as petroleum distillates, may be readily removed by ISSV from the unsaturated soil zone. A free-liquid phase (e.g., jet fuel or gasoline) floating on the water table may be removed, although the rate may be slower than collection in a recovery well. ISSV would then become an option for removal of residual contamination from the unsaturated zone.

Contaminants which are more dense than water, such as TCE and PCE, present a special problem if groundwater is present at the spill site. If the spill has already reached groundwater, the solvent may sink through the saturated zone and "pool" at a clay layer or bedrock that prevents further downward movement. The solvent will then slowly dissolve in the overlying groundwater. ISSV will remove the contaminant from air-filled pores in the overlying soil, causing volatilization of the contaminant from the water and continuing dissolution of the solvent "pool." ISSV would thus result in a slow, nearly constant removal of the solvent from the soil. However, the true source of the contamination, the solvent "pool" below the water table, will be effectively shielded from remediation.

d. Mixtures

Complex mixtures of contaminants may be vented successfully, but removal rates of individual contaminants will vary. Petroleum distillates, such as gasoline, kerosene, and jet fuel, are composed of hundreds of individual hydrocarbons. The composition of such liquids is often described as a boiling range or fractional distillation curve. Because the hydrocarbons in petroleum-derived fuels possess similar air-water partitioning qualities, removal rate by ISSV is primarily determined by vapor pressure, which is related to boiling point. During ISSV, therefore, the extracted gas will initially consist primarily of low-boiling compounds and the distribution of compounds will shift toward the higher-boiling constituents as the low-boiling compounds are removed from the contamination zone. As ISSV progresses, the rate of contaminant removal will become slower.

Mixtures of solvents may behave less predictably, particularly in the case when some constituents (e.g., acetone) are miscible with water. These compounds may be removed at a relatively constant rate during ISSV, while the rate of removal of other contaminants (e.g., benzene or TCE) declines from an initially high value through the venting operation (Reference 7). Because the behavior of mixtures is complex, characterization of the individual constituents is required before

attempting to predict the rate of remediation of a contamination zone containing mixed VOCs. The complexity of behavior also makes extrapolation from the initial ISSV rates of such a mixture to a long-term operation highly uncertain.

2. **Surface Features**

One of the major advantages of ISSV is that it can be used in areas that contain man-made structures. Installation of each individual vent well requires only a few square feet of area. Vertical wells or venting trenches can often be placed next to building foundations, pipelines, or other structures as long as they are accessible to drilling equipment. Vents may also be installed through pavement. In fact, the presence of a surface covering may enhance air flows through a contamination zone (Section VI.A.4.e). ISSV may be especially attractive from the standpoint of cost in built-up areas, where excavation costs would necessarily include destroying and rebuilding structures.

3. **Site Geohydrology**

a. **Soil Characteristics**

(1) Permeability. The flow of air through a granular porous media can be described by the following form of Darcy's Law:

$$q_i = \frac{-k_r k_{ij}}{\mu}\left(\frac{\partial p}{\partial x_i} + \rho g \frac{\partial x_z}{\partial x_i}\right) \tag{1}$$

where;

q_i = air velocity or flux (L/t or L^3/L^2t)
k_r = relative permeability of soil to air (dimensionless)
k_{ij} = intrinsic permeability tensor (L^2)
ρ = air density (M/L^3)
g = gravitational constant (L/t^2)
μ = air dynamic viscosity (M/Lt)
p = pressure (M/Lt^2)
x_i = spatial coordinates (i= x,y,z, where z is the vertical coordinate)

for which M, L, and t are the quantities of mass, length, and time, respectively.

The intrinsic permeability is a property of the porous media. The relative permeability to air depends on the total porosity, moisture content and pore-size distribution, (Reference 13); however, it is most sensitive to moisture content. For example, a sandy deposit with 30 percent total porosity and a 10 percent volumetric moisture content would have a relative permeability of about 0.4, whereas the same sand at a moisture content of 20 percent would have a relative permeability of about 0.08. The extreme variability of both the intrinsic and relative

permeabilities encountered in natural systems requires the collection of site-specific data. Since the specific discharge of air is directly proportional to the product of the intrinsic and relative permeabilities, the success of any soil-venting project depends critically on accurate estimates of these parameters.

The product of the intrinsic and relative permeabilities is referred to as the air permeability. Because air permeability controls the flow of air through soil, it is of most importance in soil venting. Three general methods are available for estimating air permeability; (1) computations using existing estimates of intrinsic and relative permeabilities, (2) laboratory testing, and (3) *in-situ* testing.

At many sites, the only information available will be estimates of hydraulic conductivity (K) resulting from groundwater pumping/slug tests or laboratory tests of saturated samples. The intrinsic permeability may be found from this information using:

$$k_{ij} = K_{ij}\frac{\mu}{\rho g} \tag{2}$$

where K_{ij} is the (water) hydraulic conductivity and μ and ρ refer to water viscosity and density.

The relative permeability can be calculated using empirical relationships such as the one developed by Brooks and Corey (Reference 13).

$$k_r = (1-\theta_e)^2\left(1-\theta_e\frac{2+\lambda}{\lambda}\right) \tag{3}$$

where the effective porosity, θ_e, is

$$\theta_e = (\theta_w - \theta_r) \,/\, (\theta - \theta_r) \tag{4}$$

where;

θ_w = volumetric soil moisture content,
θ_r = residual volumetric moisture content,
θ = total porosity,
λ = pore-size distribution index.

The pore size distribution index can be estimated using Table 2, which was developed using data from Brooks and Corey (Reference 14). The value of λ ranges from about 1.8 for poorly sorted material to 4 for very clean uniform sands. A value of 2.4 is appropriate for sandy soils. Residual moisture contents range from about 2 percent for very coarse sand to 25 percent for fine textured soils. A value of 5 percent is appropriate for medium to fine-grained sandy soils.

TABLE 2. PORE SIZE DISTRIBUTION INDEX (λ) FOR VARIOUS POROUS MEDIA (REFERENCE 14)

POROUS MEDIA	λ
Volcanic Sand	2.3
Glass Beads	7.3
Fine Sand	3.7
Touchet Silt Loam	1.8
Fragmented Mixture	2.9
Berea Sandstone	3.7
Hygiene Sandstone	4.2
Poudre River Sand	3.4
Amarillo Silty Clay Loam	2.3

Because intrinsic permeability is independent of fluid type, it has been used for decades in flow evaluations for water, oil, and gas in the petroleum industry. It is generally expressed in darcys (1 darcy $\approx 10^{-8}$ cm^2).

Ranges of typical values of hydraulic conductivities and intrinsic permeabilities for different soil and rock types are shown in Table 3. In general, hydraulic conductivities decrease with decreasing particle size in soils. Soils where venting has been demonstrated successfully are predominantly sands and gravels, with measured (water) hydraulic conductivities of about 10^{-3} cm/second. However, silt and clay soils with hydraulic conductivities ranging from 10^{-5} to 10^{-7} cm/second were reported to be successfully vented by Agrelot et al. (Reference 15), and Bennedsen (Reference 8) reported successfully vented soils with conductivities as low as 10^{-8} cm/second.

In rock, hydraulic conductivity is often due to secondary permeability (i.e., flow through fractures or large pores). Generally, ISSV is applied to spills in soils, but ISSV has also been successful in recovery of a spill in limestone (Reference 15). Although secondary permeability of some bedrock (e.g., through solution cavities of karst limestones) may result in measured hydraulic conductivity values similar to sands for some rocks, insufficient data are available to evaluate the effectiveness of ISSV in rock or subsoils in which permeability is due to fractures.

TABLE 3. RANGES OF HYDRAULIC CONDUCTIVITIES AND INTRINSIC PERMEABILITIES FOR DIFFERENT ROCK AND SOIL TYPES (AFTER REFERENCE 16)

Subsurface Material	Hydraulic Conductivity (cm/sec)	Intrinsic Permeability (darcy)*
Unconsolidated deposits		
Gravel	10^{2} - 10^{-1}	10^{5} - 10^{2}
Clean sand	1 - 10^{-4}	10^{3} - 10^{-1}
Silty sand	10^{-1} - 10^{-5}	10^{2} - 10^{-2}
Silt, loose	10^{-3} - 10^{-7}	1 - 10^{-4}
Glacial till	10^{-4} - 10^{-10}	10^{-1} - 10^{-7}
Bedrock		
Karst limestone	1 - 10^{-4}	10^{3} - 10^{-1}
Permeable basalt	1 - 10^{-5}	10^{3} - 10^{-2}
Fractured igneous and metamorphic rocks	10^{-2} - 10^{-6}	10^{1} - 10^{-3}
Limestone, dolomite	10^{-4} - 10^{-7}	10^{-1} - 10^{-4}
Sandstone	10^{-7} - 10^{-11}	10^{-4} - 10^{-8}
Shale	10^{-8} - 10^{-11}	10^{-5} - 10^{-8}
Unfractured igneous and metamorphic rocks	10^{-8} - $<10^{-11}$	10^{-5} - $<10^{-8}$

*1 darcy $\approx 10^{-8}cm^2$.

(2) Particle-Size Distribution. A soil-characterization parameter that may be helpful in evaluating permeability and, thus, prospective venting success is the particle-size distribution. Soils are often fractionated by physical means into sands, silts, and clays, with numerous subclassifications. Soils which are composed predominantly of sands and gravels will likely be amenable to ISSV. Soils that are composed of a single particle size (i.e., well-graded) are likely to possess more uniform pore characteristics and, thus, higher permeabilities than poorly graded soils. Particle-size distributions, which may be obtained by sieve analysis, reported in the literature (e.g., Reference 17) generally distinguish between the gravel and sand fractions. However, silt and clay fractions are often combined. This results in analyses that supplement soil descriptions and are useful in estimation of permeabilities for coarser-grained materials, but that cannot be used to distinguish among soils that may have low to moderate permeabilities.

(3) Moisture Content and Air-Filled Porosity. Moisture content and air-filled porosity of soils are important in that both affect the soil-vapor permeability. The air-filled porosity, which is the total pore volume of the soil minus the volumetric water content, is directly related to soil permeability because air movement cannot occur through water-filled pores.

Total porosities reported in several field and laboratory ISSV tests range from 28 to 50 percent (volume/volume). In some soils, however, moisture may represent a significant fraction of the total porosity. Information on the water-filled porosity of the soil may be important in estimating whether soil zones may be only partially vented due to partial filling of soil pores by water. Water content might be anticipated to change as dry air is forced through soil during the venting process. However, Anastos et al. (Reference 18) did not find significant changes between core samples collected before and after a venting test, and little change was noted in ISSV soil-moisture measurements made during the Hill Air Force Base demonstration (Volume III). Soils with high moisture content will more likely yield liquid water while venting; therefore, an air/water separator is required to protect the system.

(4) Soil Temperature. Because the vapor pressure of a contaminant in soil increases exponentially with temperature, ISSV is more effective in warmer soils. In the absence of heat injection, the soil temperature is essentially constant (below the uppermost few feet) at the mean annual air temperature. This value may vary as much as 20°C between Minnesota and Florida, resulting in a 4- to 5-fold difference in equilibrium contaminant vapor pressure between these geographic extremes. This factor must be taken into account in attempting to project rates of

ISSV remediation when extrapolating from one site to a similar one in a different region. However, the effect of temperature may be far less significant than that of soil permeability, which could vary by several orders of magnitude between sites.

b. Soil Heterogeneities

While some soils are fairly uniform in characteristics throughout the depth of a spill, regions of markedly different soil composition may occur. These may be either regions of higher permeability within a less permeable matrix (e.g., gravels and coarse sand lenses within glacial tills) or regions of lower permeability within a more permeable matrix (e.g., clay layers and lenses within sandy deposits). Potential effects of such heterogeneities are threefold:

- Alteration of contaminant distribution;
- Alteration of air flows; and
- Formation of zones of locally different water saturation.

The distribution of spilled liquids may be affected significantly by soil heterogeneities. Solvents and petroleum liquids may be retarded in their downward penetration by a clay layer, and thus tend to "pool" at the surface of clay. This collection at the surface is enhanced by the tendency of clay layers to contain a higher moisture content, due to increased capillary tension, than a surrounding, more permeable, soil material.

Clay layers and lenses may be far less permeable than the surrounding soil. If so, air flow within such a layer may be minimal during venting. If a contaminant has penetrated a clay layer, its removal during venting will be controlled by the diffusion rate of contaminant vapor through clay into the adjacent, more permeable soil zone, as vapors in the soil zone are removed in the vented air stream. ISSV of contaminated clay layers has been demonstrated successfully when: (1) vent wells are placed sufficiently close together for effective removal of air from the soil adjacent to the clay and (2) ISSV is continued for long enough to permit diffusion of contaminant vapors to progress toward complete removal from the clay layer.

Layers of relatively low permeability may also effectively prevent air flow from a vent well, screened above or below a layer, to contamination on the other side of the layer (e.g., Reference 19). An oily zone, where soil pores are filled with an immobile oil that reduces air permeability, has been observed to have the same effect (Reference 18).

c. **Location of the Water Table**

ISSV is only effective in unsaturated soils, where soil pores are filled with air that can be drawn into the extraction well under the force of a pressure gradient. Commonly, the depth at which soil is saturated is considered to be the water table. More accurately, however, the water table is defined as the point at which the fluid pressure is exactly equal to atmospheric pressure. This depth is equivalent to the level at which water stands in an open well or pipe that penetrates the soil just deeply enough to encounter water at the bottom (Reference 16). Saturated conditions are often found for several feet above the water table due to capillary forces.

Vents are commonly installed either vertically in boreholes or horizontally in trenches. For ISSV using vertical vents to be effective, the depth from ground surface to the water table should be at least 10 feet. This depth reduces short-circuiting of air movement from the surface to the extraction wells. In certain situations, the water table may be artificially lowered by groundwater pumping, if necessary, to enlarge the unsaturated zone. However, depression of the water table may spread contaminants further vertically and may increase contamination reaching the groundwater (Reference 20). Horizontal vents in trenches with a polyethylene surface barrier have been used to remediate a site with a water table at a depth of 6 to 8 feet (Reference 21).

When vent pipes intersect the water table, water will be drawn up a distance proportional to the applied vacuum pressure. In addition, the nearby water table will be drawn up in an inverted conical shape caused by the reduced pressure field around the well. Care must be taken during system design to avoid inducing a vacuum that draws uncontaminated groundwater into a contamination zone.

Under some circumstances, it may be useful to provide a longer well screen than necessary, extending throughout the unsaturated zone. For example, in the design of a well for recovery of floating contamination (e.g., gasoline) from the surface of the water table, such extension will permit subsequent use of the well during ISSV.

In regions that experience considerable amounts of rainfall or snowmelt, saturated conditions may occur in the soil above the water table (i.e., an inverted water table) on a transient basis due to infiltration from the surface. ISSV may have to be curtailed in this portion of the soil during such periods.

Saturated zones may also appear either on a seasonal or permanent basis at depth above clay layers (i.e., perched water tables). ISSV will not be effective in these saturated zones due to the lack of air-filled pores through which contaminant vapors may move. If a perched water table is both

permanent and sufficiently extensive to underlie an entire contamination zone, it may serve as the effective lower barrier to vapor transport in the venting process.

B. OTHER FACTORS IN TECHNOLOGY SELECTION

1. Cost

The costs of ISSV systems are site-specific, depending mainly upon the size of the spill and duration of the remediation. Capital costs are usually low, with major factors including the number and depth of vents, blowers, valving, piping, instrumentation, and air emissions control if necessary (References 8 and 22). Operating costs are also usually relatively low, since these systems are not labor-intensive. Major operating costs are sampling, sample analysis, power, maintenance, and emissions control (References 8, 18, 22, and 23). Emissions control can add significantly to operating costs. Other major costs in site cleanup will include preparation of cleanup plans, permitting, and performance monitoring (Reference 21).

In preparation of cost estimates, values should be determined for the following items:

a. Site Characterization

- Drilling
- Sampling
- Sample Analysis
- Soil-Gas Analysis

b. Technology Selection and Permitting

- Preparation of Conceptual Designs
- Analysis and Comparison
- Regulatory review

c. Testing

- Bench Tests
- Pilot Test
    - Vent and Pressure Monitoring Well Installation
    - Equipment
        - Blower
        - Piping
        - Demisters
        - Emissions Controls
        - Instrumentation
    - Assembly
    - Operation
    - Sample Analysis

d. Implementation

- Full-Scale Design
- Vent and Pressure Monitoring Well Installation
- Equipment
  - Blower
  - Piping
  - Demisters
  - Emissions Controls
  - Instrumentation
- Operating Costs
  - Manpower
  - Electricity
  - Fuels
  - Sample Analysis

e. Termination of Operation

- Confirmatory Sampling
- Sample Analysis
- Equipment Demobilization

Because costs of ISSV applications are site specific, it is difficult, and possibly misleading, to provide specific cost values for each of the elements listed above. Each operator is far more qualified to prepare realistic cost values for items such as drilling, sampling, and sample analysis at a particular site. Section VII presents an economic analysis model for those costs of venting which should be common to most systems. This spreadsheet estimates costs of the above-ground equipment of ISSV systems. This model is used to estimate capital and operating costs for the blower and emissions control given the size of spill and time required for remediation.

2. Legal Implications

a. Patents

ISSV technology is in widespread use by many vendors, and its relative simplicity makes it feasible for some installations to design and operate their own systems. However, the status of patents granted in this field must be considered before the technology is applied or a vendor is contracted.

ISSV is the subject of several patents, of which U.S. patents 4,183,407; 4,593,760; and 4,765,902 are known examples. Each installation should consider the applicability of these and other patents to planned remediation and act accordingly.

The Air Force can be held liable for damages resulting when a contractor is sued for violating a patent. It is the recommendation of HQ AFESC that to reduce the risk of liability when implementing ISSV technology, an installation should:* (1) Arrange an agreement with a patent holder. This has been done by DOE's Savannah River Plant, which bought a license from Terra Vac, Inc.** The cost of that license was based on an estimate of the total cost of using ISSV technology for remediation of sites at the plant. (2) Contract with a company that holds a license for using ISSV technology. Further details of patent issues on ISSV are given in a letter from a patent attorney at HQ MSD/JAN to HQ AFESC, which is included in Appendix A of this document. This letter concludes that patent issues will pose no problem for ISSV if normal Air Force contracting procedures, including the standard Federal Acquisition Regulation (FAR) patent clauses, are used.

b. Regulatory Requirements

ISSV, as do all other remedial technologies, must comply with a broad range of federal, state, and sometimes local regulations. Although a detailed examination of these regulations is beyond the scope of this document, several key considerations are presented below. The required level of treatment or cleanup standard should be determined before initiating a full-scale remediation.

(1) State vs Federal Jurisdiction. The U.S. Environmental Protection Agency (EPA) develops and administers regulations to protect human health and the environment under the authority of the following environmental statutes: the Clean Air Act (CAA); the Clean Water Act; the Resource Conservation and Recovery Act (RCRA); Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) as amended by the Superfund Amendments and Reauthorization Act (SARA); the Safe Drinking Water Act; and the Toxic Substances Control Act (TSCA). EPA can authorize states to administer the regulatory programs. In some cases, notably CAA requirements, regulation varies significantly among states. The state program, therefore, is the key standard of compliance requirements.

*Personal communication from Captain M. G. Elliott, August 1989.

**Personal communication of Captain M. G. Elliott with Brian Looney of DOE Savannah River Plant, 13 September 1989, and with James Malot of Terra Vac, 12 September 1989.

In some cases, local governmental agencies have also developed regulatory programs. Some of the state and local programs are in place only through informal agency guidelines and interpretations. Communication channels must be established with local or state agencies to track pertinent policies and regulations as they evolve. For example, the National Air Toxics Information Clearinghouse, established by EPA, publishes a computerized data base on toxic air pollutants, hard-copy reports of the data base, special topical reports, and a quarterly newsletter. Data on federal, state, and local air toxics programs are expanded and updated on a regular basis. Each state has a department (e.g., Department of Environmental Management, Department of Environmental Protection) responsible for environmental regulations and can provide guidance in monitoring and implementation of the ISSV.

(2) Regulatory Definition of Endpoint. The type of cleanup standards for a specific site may be a determining factor in the applicability of ISSV. Danko (Reference 24) suggested that ISSV may not be applicable if overall cleanup limits are unrealistically low, if compound-specific limits are required, or if verification with statistical soil-sampling grids is required. ISSV technology is more likely to be successful if total concentration limits are high and closure is verified by vapor analyses or average soil concentrations. However, a modeling study by Johnson et al. (Reference 2) indicates that low, compound-specific limits may not be a determining factor in application of ISSV for fuel mixtures. Results of successful closure using groundwater contaminant levels have also been reported by Payne and Lisiecki (Reference 25). Verification sampling is discussed further in Section VI.D.1.

A heterogeneous distribution of residual contamination may result if the ISSV operation is halted before complete contaminant removal. Contaminant levels may be reduced to essentially zero in zones where air movement has been rapid, with higher contaminant levels still present in or immediately adjacent to clay lenses or bedrock. Guidelines for solid waste disposal (Reference 26) specify comparison of an action level to a mean residual concentration determined within a "uniform area" via a standard statistical test. A zone of lower permeability might be defined as a "uniform area," and samples within that zone might be composited and treated separately from the bulk soil. Other site-cleanup agreements have specified that any contamination areas in which pooled sample analyses exceed the action limit will be remediated to the action level. The EPA plans to i ,ue a technical resource document "Batch-Type Adsorption Procedures for Estimating Soil Attenuation of Chemicals" (originally scheduled for April 1990). This document may provide new standards and guidelines for site cleanup that are pertinent to the soil venting technology.

The mandated cleanup requirements for a contaminant may vary from state to state. Therefore, the appropriate state regulatory department must be consulted.

(3) Air-Permitting Considerations. The ISSV technology may discharge VOCs into the atmosphere. Potential exposure levels associated with these activities must be assessed in order to design emission control strategies, and protect workers at the site, as well as the general public. Application of the technology will require assessment on a site-specific basis, and must address local and state regulations governing emissions and permitting. It may sometimes be more economical to operate an ISSV system at a lower venting rate to keep daily VOC emissions below threshold levels. EPA regulations for the monitoring and control of emissions at hazardous waste treatment, storage, and disposal facilities may also affect ISSV operations if these facilities are necessary to handle soil disposal during drilling of vent wells or if the soil is contaminated from an accidental spill during operations.

The Clean Air Act has been the basis for regulation of air-pollutant emissions to protect human health and the environment. Amendments to the Clean Air Act, passed in 1970, give EPA the authority to delegate responsibility to state and local governments for prevention and control of air pollution at the source. Recently, EPA has proposed several amendments and guidelines that may be relevant to ISSV. If permits for ISSV are required, special permitting procedures may apply. Such permitting procedures, as established for facilities conducting research on the storage, treatment, or disposal of hazardous wastes, will allow greater flexibility without requiring frequent permit modifications. The EPA has also proposed amendments to the RCRA landfill, surface impoundment, and waste-pile closure rule to allow the use of site-specific closure requirements. Waste and site characteristics, potential pathways of hazardous material migration, and health effects will be addressed in regulations that were proposed in October 1989 and that were placed on hold until Fiscal Year 1991.

Federal, state, and local agencies have established procedures for issuance of permits, and for monitoring compliance with existing regulations. The jurisdictions of these various governmental levels are discussed in Section II.B.2.b.(1). Generally, however, the state has final authority.

(4) Potential Effects on Groundwater. The EPA and the U.S. Geological Survey (USGS) are the two primary federal agencies responsible for groundwater programs. Over 25 other agencies and offices are involved in groundwater-related activities, and 16 federal statutes authorize programs relevant to groundwater protection. In addition, all 50 states have groundwater-protection programs

that vary in both approach and strength. Primary responsibility for groundwater protection lies with the states, based on a strategy plan issued by the EPA in 1984. Superfund legislation has set cleanup standards for the nation's worst hazardous waste sites, including groundwater cleanup standards.

A final rule was expected in July 1990 on an amendment to the groundwater-monitoring regulations that would support the early detection of leaks and better tailor the groundwater-monitoring regulations to site-specific conditions. Regulations to amend the technical and procedural requirements for conducting corrective action to clean up significant releases to groundwater from regulated hazardous waste units at operating, closed, or closing RCRA facilities and the requirements for implementing remedial action, remedy selection, and corrective measures were expected in a final ruling in June 1991. These proposed amendments could have significant impacts on the application of ISSV technology if the groundwater should be contaminated during the operations.

C. OTHER *IN SITU* REMEDIATION TECHNOLOGIES

ISSV has limited application for semivolatile and nonvolatile contaminants and for conditions of aquifer contamination; therefore, soil venting may not provide a complete solution for a site with a mixture of contaminants. Other *in situ* techniques that may be applicable for these VOC-contamination sites include (1) soil flushing, (2) microbial treatment, (3) chemical treatment, (4) vitrification, and (5) radio-frequency heating. These techniques, which are described briefly below, are reviewed by Lee et al. (Reference 27), Sanning and Lewis (Reference 28), and Thomas et al. (Reference 29), who provide sources of detailed information.

1. Soil Flushing

Soil flushing is a process by which water or an aqueous solution is passed through the contaminated soils, solubilizing the contaminants. The solution is then pumped to the surface for treatment. Water flushing is reportedly effective for medium solubility organics (octanol/water partition coefficient ranging from 10 to 10,000), including lower molecular weight halogenated hydrocarbons such as TCE and PCE. Surfactant solution flushing may be used to remove hydrophobic organics. However, surfactant flushing by itself has not proven capable of restoring soils to final cleanup levels, and treatment of the contaminated surfactant solutions is difficult. Soil flushing promises low treatment costs, in comparison to excavation, for wastes that can be so treated. Despite the repeated success of engineered surfactants to clean contaminated soils in laboratory column tests, no data were obtained in a U.S. Air Force test at Volk Field (ESL TR 87-18, Surfactant-Enhanced *In Situ* Soils Washing, Sept. 1987) to statistically confirm *in situ* soils washing as a viable method of soil decontamination.

2. Microbial Treatment

Microbial treatment, or biorestoration, involves either altering conditions in the contaminated soil to enhance the activity of microorganisms naturally present or adding adapted organisms to the soil for biological degradation of the hydrocarbon contaminants. Laboratory and field tests have shown that fuels and chlorinated solvents are subject to microbial degradation. Fuels have been degraded under aerobic conditions, whereas the microorganisms causing degradation of several chlorinated contaminants act under anaerobic conditions. This technology has been most successful in removing aromatic compounds from the saturated zone. This process is largely unproven for unsaturated zone treatment. The recent use of ISSV to enhance biodegradation above the water table has shown more promise than water-based oxygen delivery methods. This technology requires more permeable soils to ensure adequate distribution of oxygen and nutrients (Reference 30).

3. Chemical Treatment

Chemical treatment refers to processes where chemicals are added to the soil to undergo reactions with specific constituents in the soil. Oxidation and reduction reactions may prove useful for destruction of fuels and solvents. Oxidation of organics may be achieved by addition of chemicals such as ozone, hypochlorites, or hydrogen peroxide. Hydrogen peroxide treatment provides the added effect of acting as an oxygen source for microbial degradation. A disadvantage with this technology is that the injected chemicals cannot be limited to oxidizing just the organic contaminants. Reducing agents may be added for treatment of chlorinated organics; however, this treatment has not been proven and is very costly.

4. Vitrification

In situ vitrification is a process where electric current is passed through contaminated soil, heating it to melting, then cooling it to form a hard glassy material with low leachability. The process is mainly used for immobilization of radionuclides, but is reportedly successful with organics. Some organics may not totally oxidize prior to release from the soil, making off-gas treatment necessary. A disadvantage of this technique is the high energy requirement.

5. Radio-Frequency Heating

Radio-frequency (RF) heating is an emerging technology which heats the contaminated soil by passing electromagnetic waves through the area. The waves are generated by placing vertical electrodes into the formation and exciting by an RF generator. Decontamination of the organics is caused by enhanced volatilization and steam distillation at temperatures during treatment at 150° to 200°C. Off-gases must be collected and treated. Advantages of this process are removal of higher

boiling compounds which cannot be removed with ISSV and reduced treatment times when compared to ISSV. A pilot test in sandy soils achieved 97 percent removal of JP-4 in two weeks (Reference 31). HQ AFESC was to have conducted a pilot-scale test of RF soil decontamination in clay soils during FY 1990-1991 to determine energy requirements and estimate full-scale costs.

A comparison of these technologies with ISSV is presented by Ghassemi (Reference 6), McLearn et al. (Reference 5), and Towers et al. (Reference 4). In general, these articles present the cost of ISSV as low; containment - low to moderate; biodegradation, excavation, and leaching - moderate; and vitrification - high.

SECTION III

SITE-CHARACTERIZATION STUDIES

Before beginning an ISSV remedial operation, the site must be characterized from two standpoints: contaminant distribution and geohydrology. The latter category includes those factors that can greatly affect the success of an ISSV operation, including: (1) soil characteristics—including permeability, (2) depth to water table, (3) presence of perched groundwater or other saturated conditions, and (4) presence of clay lenses and other heterogeneities. These factors are developed in more detail in Section III.A.

The Air Force Installation Restoration Program (IRP) Phase II site-characterization activities may provide the majority of this information. If data gaps are found during the process of evaluating alternate remediation strategies, additional characterization work may be deemed necessary.

A. PRELIMINARY INVESTIGATIONS

1. Previously Collected Information

General information on site geohydrology can often be obtained from past studies. Soil typology may be available from county soil surveys which predate Air Force activities at the site. Stratigraphic information of the upper soil layers, as well as information on regional groundwater, may be available on a large scale through the USGS. Logs, written notes, or verbal comments from local well drillers can be of assistance in evaluating likely subsurface conditions. Logs of any monitoring or water production wells installed near the Base should be examined. If surface structures exist nearby, soil boring logs, engineering soil-test results, and foundation-excavation logs may also be available.

2. Soil-Gas Surveys

Although anecdotal information may be available to assist in delineating the bounds of contamination resulting from a single major spill, additional data are generally needed to define the bounds of the contamination zone. For volatile contaminants, including jet fuel, gasoline, other light petroleum distillates, and degreasing solvents, a soil-gas survey can provide a substantial amount of preliminary information on the lateral extent of contamination for relatively little cost.

a. Methodology

Vapors from VOC contamination in the subsurface partition into the air via soil pores at the boundary of the contamination zone. These vapors diffuse upward through the soil to the surface. In a soil-gas survey, vapors from subsurface contamination are often collected from several

locations at or near the soil surface. The collected vapors may be identified to determine the nature of the subsurface contamination. The vapor concentration is determined at each point; and this concentration is assumed to be roughly related to the concentration of contamination in the soil below.

Soil-gas surveys may involve either passive or active vapor collection. Passive collectors consist of sorbent traps (e.g., activated carbon or Tenax®) that are either placed on the surface or buried to a depth of several inches. Vapors that diffuse past the collector are sorbed and retained. Traps are retrieved after several days and returned to a laboratory for analysis by gas chromatography (GC) or gas chromatography-mass spectrometry (GC-MS).

Active gas collection involves installation of hollow probes, usually to a depth of 2 to 10 feet. Soil vapors are withdrawn by means of a vacuum pump; the vapor stream is either directed past a sensing device to determine contaminant concentration or a subsample is withdrawn for analysis. Shallow probes may be driven into the soil manually, while deeper probes usually require a hydraulic press. An alternate method for collecting shallow samples is to create narrow-boreholes with a plunger bar equipped with a slide hammer. A tube is then inserted into the hole and sealed, and vapors are withdrawn for analysis.

b. Gas Analysis

Analytical techniques for gas analysis in the field may involve gross measurement of total contaminants or separation and quantification of individual constituents by GC. Total contaminant detectors, such as the Photovac TIP® or the HNu®, provide semi-quantitative measures of contamination within seconds, while GC separations may require 5 to 20 minutes per sample. Portable GC instruments, although slower, possess the advantage of providing tentative contaminant identification by comparison of chromatographic retention times with standards. By providing separation of potential interferences, such as methane, GC instruments also avoid potential errors in contaminant quantification. One successful technique uses a total contaminant detector as a screening device, followed by GC analysis of samples showing positive results.

Detectors for both total contaminant measurement and GC analysis employ either flame or ultraviolet light-induced ionization of contaminant gases. The Foxboro OVA®, which uses a flame ionization detector (FID), can be used either to detect total contaminants or individual constituents by channelling the gas flow through a chromatographic column, prior to the FID. The photoionization detector (PID), which is used in the Photovac TIP® and the 10S series of field-

portable GC instruments, can detect certain photoionizable contaminants at low ppb levels. Other field-portable GC instruments and total-contaminant detectors that utilize FIDs and PIDs are available.

Both the FID and PID possess advantages and disadvantages. The PID is highly sensitive to certain VOCs, including trichloroethylene (TCE), perchloroethylene (PCE), and benzene. Instruments that use FIDs are less sensitive, but possess more uniform sensitivities to a broader range of hydrocarbons than do PIDs. PID responsiveness to different contaminants may vary by several orders of magnitude. Although soil moisture sometimes produces a negative interference, PID instruments are insensitive to methane, which is often present at high levels in the soil and which gives a positive response to FIDs (such as the OVA®). High methane levels in areas of substantial microbial activity may produce false-positive indications of contamination with an FID, unless used in conjunction with a chromatographic column to provide separation of methane from VOCs as mentioned above.

Several soil-gas survey firms employ laboratory GC or GC-MS instrumentation in portable trailers for transport to a soil-gas survey site. This method can produce gas characterization and quantification data comparable in reliability and sensitivity to that of analytical laboratories, although at greater expense than field-portable instrumentation.

c. Advantages and Disadvantages

Soil-gas surveys can provide rapid and relatively inexpensive information on the lateral extent of VOC contamination in the soil, as well as the locations of areas of highest contaminant levels. A survey may also be conducted near buildings and other surface structures, or in paved areas, with minimal disruption of normal operations. The information obtained may be used to guide locations of exploratory boreholes, as well as estimate the extent of vent well field required.

Results of a soil-gas survey, however, can only be interpreted through a good understanding of the subsurface geohydrology. Several factors can affect transport of vapors to the near-surface region sampled by probes or passive collectors. Clay, perched water, or other zones that are relatively impermeable to vapor transport and that occur between subsurface contamination and the surface can prevent upward vapor movement, resulting in false negative readings. Biodegradation can deplete soil vapors of some readily degradable contaminants, such as benzene. In fact, low O_2 and high CO_2 in soil gas may be a good indicator of fuel hydrocarbon contamination.

Diffusing vapor concentrations decrease toward the surface, and probes installed at insufficient depth may not detect them; a general rule is that probes should be installed to about 10 percent of the depth to the water table to ensure detection. Infiltration of rainwater or snowmelt during the period before the survey can displace soil contaminant vapors, resulting in false negatives if insufficient time is allowed for such vapors to recharge the soil pores. Even when conducted properly and interpreted in conjunction with sufficient understanding of subsurface geohydrology, a soil-gas survey provides information only on the relative concentrations of contaminants. Near-surface gas concentrations cannot be used to calculate total contamination concentrations in the subsurface with any degree of reliability. Moreover, soil-gas surveys do not yield information on the depth of contamination. Despite these limitations, soil-gas surveys provide a substantial amount of preliminary information on the lateral extent of contamination for relatively little cost, and can guide exploratory borings and preliminary scaling and design of the venting system.

B. EXPLORATORY BORING

Although review of existing information and conducting of a soil-gas survey will provide valuable information, it will not be sufficient to determine the feasibility of ISSV at the site. One or more soil borings will be required. Borings will assist in (1) determination of the depth and level of contamination; (2) collection of samples for evaluation of soil characteristics; and (3) identification of the presence of geohydrologic features that may affect venting success. Borings may also be used in preliminary pressure tests for measurement of soil permeability (discussed in Section III.C.).

1. Borehole Installation

a. Location

One boring should be located at or near the likely zone of maximum contaminant concentrations, determined either from information relative to the route of contamination (e.g., spillage) or from a preliminary soil-gas survey. Borings should also be located at positions that may clarify uncertainties of the underlying geohydrologic conditions, e.g., the presence of a possible clay layer or lens, an underlying zone of potentially higher permeability, or perched water. The number of preliminary borings will depend on both the known degree of uniformity of the geohydrologic setting, and the known or suspected extent of contamination.

b. Depth

Exploratory borings should penetrate deeper than the suspected depth of contamination to assure that the lower extent is bounded before design of the venting system. If a spill is suspected to have moved downward to a low-permeability layer, boring into that layer is necessary to determine

the extent to which penetration has taken place. However, care should be taken to avoid penetrating an overlying aquiclude (a zone preventing water penetration) into a lower regional water table, because the borehole could then serve as a means of contaminant transport to this lower aquifer. Use of a VOC-screening instrument can be of assistance in making in-field decisions as to the depth to cease drilling.

c. Methodology

Generally, boring with a continuous-flight auger is the most useful technique for boring down to a depth of approximately 150 feet through unconsolidated material. Use of a hollow-stem auger permits sampling through the auger without removal from the ground. Cable-tool drilling may be preferable in some circumstances, such as in "heaving" sands. Air-rotary methods may be used for deeper drilling or when the contaminated subsurface material cannot be penetrated by an auger. Because of potential contamination, methods employing drilling fluids should never be used. Care should be taken to ensure that liquids from any source (e.g., lubricants from the drill rig) never enter the borehole to avoid introducing contamination and confounding results of the exploratory boring.

Safety precautions appropriate for work in a contaminated site should be enforced throughout field operations. Cuttings from drilling operations should be collected and disposed in accordance with applicable regulations.

d. Logging

To assess the geologic character of the site, the borehole should be logged during installation by a professional geologist. Although some information can be obtained from auger cuttings, inspection of discrete samples is far preferable because it ensures accurate depth determinations and reduces the likelihood of missing thin stratigraphic features. A continuous split-barrel sampler advanced through a hollow-stem auger is ideal for logging.

Observations made during logging should include descriptions of soil type, texture, color, moisture, odor, and any unusual features. Depth of stratigraphic variations should be determined with sufficient accuracy to ensure that vent screens can be positioned accurately relative to clay lenses, saturated zones, or other modifiers of air flow. Measurements of contaminant vapors obtained as the sampler is opened can provide qualitative information on the presence of contamination.

2. Sampling and Analysis

Soil samples collected from exploratory borings are necessary for determination both of vertical contamination profiles and of soil characteristics.

a. Sampling Methodology

Soil samples for determination of both chemical contamination and soil characteristics should be collected either using a split-spoon or, in soft unconsolidated materials, a pushed tube (i.e., Shelby) sampler. Samples are usually collected at 5-foot intervals during boring unless knowledge of the likely contaminant distribution dictates more or less frequent sample collection.

Once collected, samples for contaminant analysis should be handled by approved methods, such as those specified in USEPA (Reference 26). Subsamples should be removed and transferred to sampling containers with minimal handling or mixing to minimize opportunity for VOC loss. Although not yet a USEPA-approved method, brass-spoon liners that may be removed, capped with Teflon® film and plastic seals, and shipped on ice to an analytical laboratory have been successfully used to minimize loss of VOCs during sampling. If sample analyses will be used for regulatory compliance purposes, appropriate QA/QC procedures must be employed, including proper cleaning methods, use of appropriate blank samples, storage, shipment, and chain-of-custody procedures. A useful description of these procedures is found in USEPA (Reference 26).

Samples for soil characteristics should be removed from a split spoon or Shelby tube to tared containers for shipment to the laboratory. Appropriate chain-of-custody procedures should be used with these samples also.

b. Sample Analysis

Not all samples collected during preliminary boring need to be analyzed. Analysis of samples for soil characteristics may be conducted on a subset representative of the major soil types found at the site. To determine VOC concentrations, an in-field screening procedure may be used to determine which samples require laboratory analysis. This may consist of surveying the sampling device with a total VOC analyzer (e.g., a Photovac TIP® or HNu®) upon collection or transfer of a replicate subsample to a closed container that is then allowed to equilibrate prior to sampling the headspace. Several variations of the latter technique have been developed and used by T. M. Spittler, Director of the USEPA Regional Laboratory in Lexington, MA.

*Personal communication, T. M. Spittler to S. E. Herbes, 13 January 1987.

Several commonly used analytical procedures for chemical and soil characteristics are listed in Table 4. Although these are appropriate for contamination by JP-4, gasoline, and many common solvents, other chemical analyses may be used in particular situations. Additional soil analyses that may be applied in particular situations include bulk density and total organic carbon.

TABLE 4. APPLICABLE METHODS FOR ANALYSIS OF CONTAMINANTS AND SOIL PARAMETERS IN SOIL VENTING PRELIMINARY INVESTIGATIONS

Parameter	Method	Reference
Total petroleum hydrocarbons	No. 1-221029, Rev. 2	32
Total VOCs	624	33
Volatile aromatic hydrocarbons (BTX)	8020	26
Particle size range	D422-63	34
Moisture content	Gravimetric	35

3. Borehole Completion

Whenever possible, a vent well should be installed in the borehole as a part of the future venting system. Following logging and sampling of exploratory borings, and possibly *in situ* testing of permeability (Section III.C.), boreholes should be completed in accordance with applicable regulatory guidelines. This may involve grouting to the surface, or to above the water table with back-filling with clean sand or soil to the surface.

C. *IN SITU* PERMEABILITY TESTS

If little information is available at a site to assess the permeability of the subsurface, an <u>*in situ* permeability test</u> can provide invaluable information for assessing the probable effectiveness of an ISSV operation and designing the system. Because little published information is available concerning methods of testing and applications to ISSV, the theory and procedures for conducting a test are presented below in some detail.

1. **Background**

In situ testing can provide rapid, inexpensive, and accurate estimates of air permeability. *In situ* measurements of air permeability are more useful for designing and modeling soil venting systems than are laboratory permeability tests since they are conducted at roughly the same spatial scales.

Although a wide variety of specific methods are possible, all *in situ* tests involve the creation of a pressure stress (either positive pressure or vacuum) accompanied by measurements of the pressure distribution in the porous media and of the air-flow rate used to create the stress. Both transient and steady-state tests are possible using one or many pressure-monitoring points.

The computation of air permeability from pressure and flow rate data requires the results from mathematical models that are developed from conceptual models of the geometry and physical nature of the porous media. It is always important to review the conceptual model upon which the computations are based to assess the appropriateness of a given mathematical technique.

2. **Conceptual Basis**

A mathematical model, known as FEMAIR (Finite-Element Model for AIR transport), has been developed to describe two-dimensional flow in the vertical plane (Reference 36). Radially symmetric flow is assumed to or from a test interval in a borehole. This model was used to construct curves and graphs of dimensionless parameters that can be used to calculate air permeability from *in situ* test data. Although FEMAIR is quite general, a number of constraints were employed to develop the curves and graphs. These constraints, along with the inherent assumptions used in FEMAIR, are illustrated in Figure 3 and include:

- isotropic and homogeneous permeability distribution,
- land surface represents a constant pressure boundary,
- lower boundary is impermeable to air (i.e., water table),
- pressure changes are small enough that the air density is nearly constant (experience has shown that pressure changes less than 2 pounds per square inch do not violate this assumption), and
- relative permeability is temporally constant (i.e., test does not change moisture content).

3. **General Methodology**

The pressure stress required for *in situ* testing can be developed either by injecting air using a positive pressure or withdrawing with a vacuum. Although air injection may alter the moisture content more than vacuum tests, the effect is probably small. Mathematically, injection and vacuum

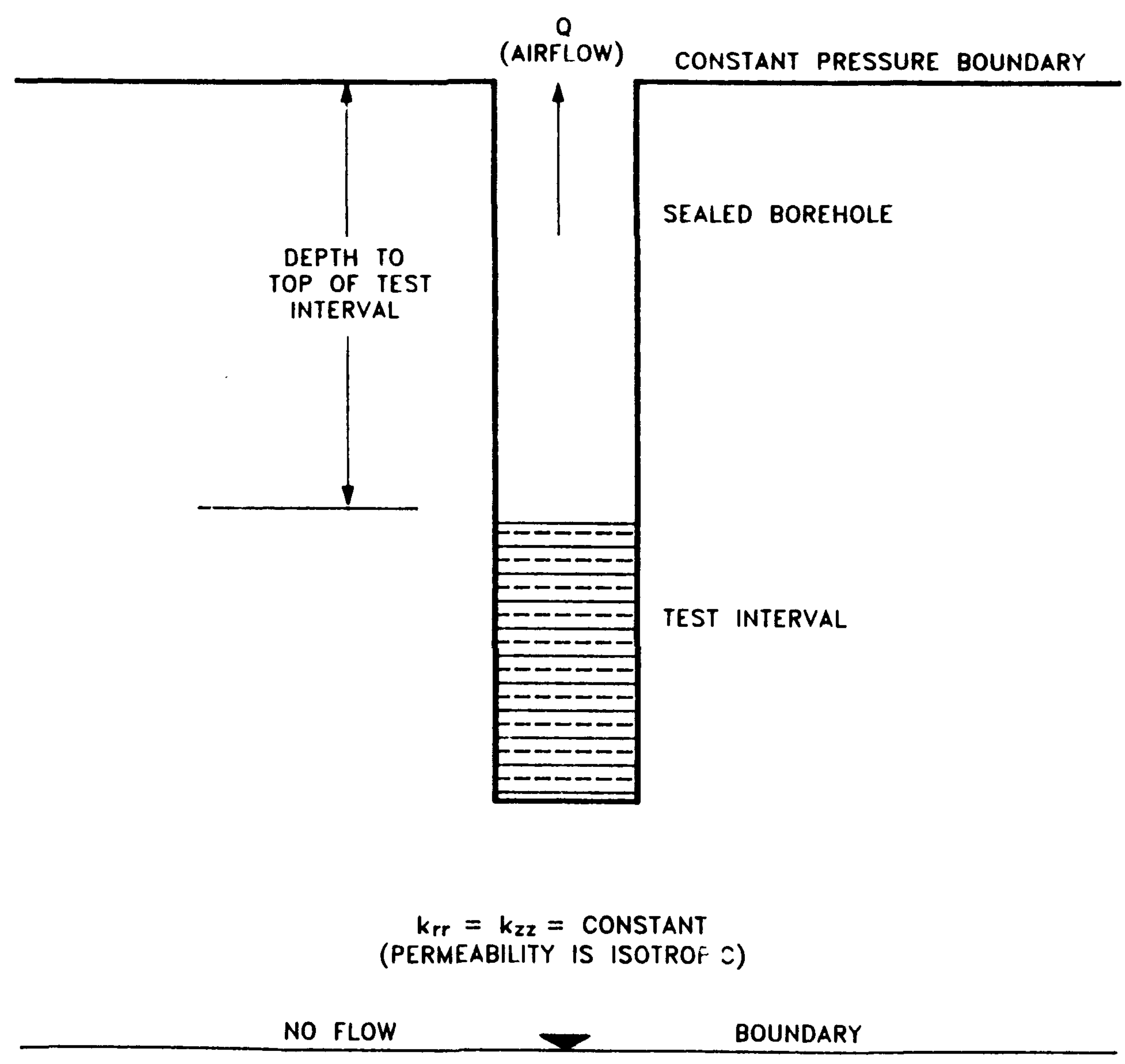


Figure 3. Geometry of Physical System Used for *In Situ* Air-Permeability Analysis.

tests are identical. Injection tests may be advantageous since compressed gas cylinders can provide a simple, inexpensive air source that can be used during site characterization when electrical power may be unavailable. Furthermore, vacuum pumps capable of both high volume and high vacuum often require additional equipment such as moisture traps. Health and safety concerns associated with emissions must also be addressed.

Both steady-state and transient tests can be conducted. The steady-state distribution of pressure depends on air permeability, injection/withdrawal rate, and geometry of the test configuration. Transient pressures are also affected by the air-filled porosity of porous media, which acts as a storage mechanism. It is possible to determine both the air-filled porosity and the air permeability with a transient test. However, a curve-matching method is used and, consequently, the estimated porosity will have a significant uncertainty associated with it. Only the air permeability can be obtained from a steady-state test. Unlike groundwater-pumping tests, steady-state air pressures occur quickly (minutes for small, near-surface tests, hours for large, deeper tests). Under most conditions, the transient response is not of great practical interest and, hence, is not discussed further in this report. In addition to the uncertainty involved, the only real use of the air-filled porosity is for modeling transient pressure response.

4. Steady-State Test Using an Inflatable Packer

a. Equipment

In situ air permeability measurements can be made in a borehole using the equipment shown in Table 5. All of the components in this table are commercially available. The testing equipment should be assembled and installed as illustrated in Figure 4. Although the borehole can be constructed using any available method, a hand-operated bucket auger may be adequate for depths up to 3 meters. The inflatable packer provides a means of sealing the borehole from land surface down to the test interval. For shallow tests, a single packer will suffice. A series of packers can be used for deeper applications, e.g., in an exploratory borehole (Section III.B.).

The pressure-monitoring tube allows accurate measurements of the pressure in the test interval using a pressure gauge located at the surface. Since only pressure changes are used for calculations, it is not necessary to correct the measurements for the weight of air inside the monitoring tube. Significant head loss can occur along the air hose during injection, thus it is very important that a separate pressure-monitoring tube be used. Some packers contain special ports which allow the pressure monitoring tube to be hydraulically connected to the test interval. In the absence of such a port, the pressure monitoring tube can be inserted inside the air hose and extended

TABLE 5. EQUIPMENT FOR CONDUCTING STEADY-STATE AIR PERMEABILITY TESTS

ITEM	QUANTITY (min)	COMMENTS
Inflatable Packer	1	None
Pressure Gauge	1	0-1 psig range
Compressed Air or Nitrogen Cylinders	3	Size No. 1
Pressure Regulator	2	None
Air Hose	1	Nominally 2.5 cm diam.
Bucket Auger	1	None

to just beyond the mandrel of the packer. The monitoring tube can exit the air hose using a tee and reamed compression fitting. The purpose of the flowmeter is to assure that a constant flow rate occurs throughout the test. The absolute flow rate can be determined by monitoring the source tank pressure and, thus, it is not necessary to calibrate the flowmeter for the temperature and pressure conditions of the test.

The optimal flow rate and, hence, the capacity of the flowmeter depends on the permeability and the length of the test interval. The steady-state pressure change in the test interval should not exceed about 2 pounds per square inch to prevent invalidating the constant air density assumption. The optimal pressure change is about 1 pound per square inch. The flow-meter capacity can be calculated by estimating the permeability and using the dimensionless graph (explained in the calculation portion of this section) with a given test interval length and a pressure change of 1 pound per square inch (6893 Pascals). The length of the test interval can be adjusted in the field to compensate for a poor initial estimate of the permeability.

b. Procedure

Three compressed-air (or nitrogen) cylinders are required for the test; one to inflate the packer, one to adjust the flowmeter, and one to conduct the test. The packer should be inflated to about 50 pounds per square inch. The flow rate should then be adjusted to the optimal value by injecting air into the borehole from one of the compressed air cylinders. The air hose should then be connected to the other compressed air cylinder to conduct the test. The absolute flow rate will

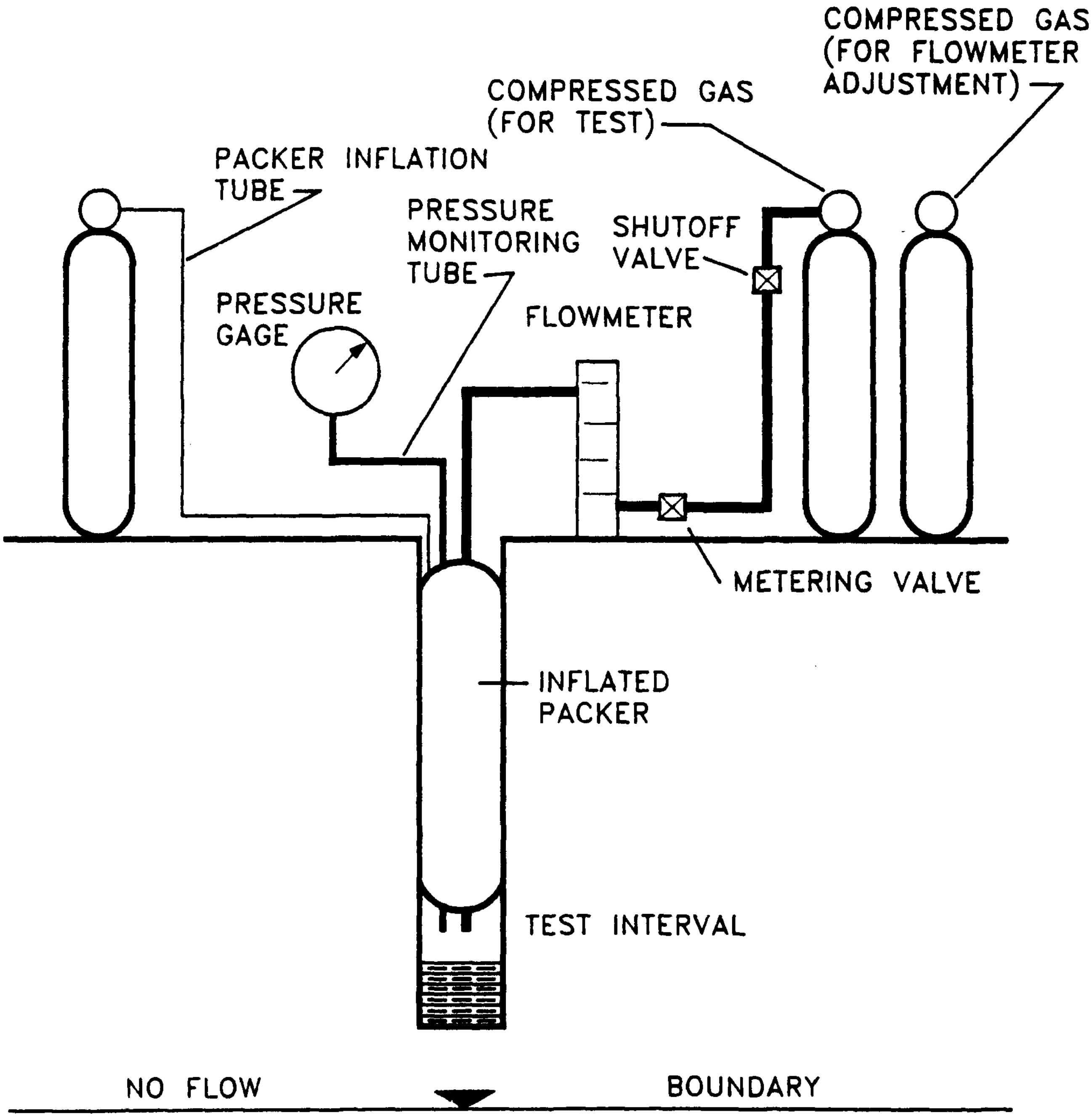


Figure 4. Equipment and Setup for Conducting *In Situ* Air Permeability Test.

be determined by the change in cylinder pressure over the time of the injection. The gas pressure is a function of temperature inside the cylinder, which will change during the test as a result of Joule-Thompson cooling. To eliminate this problem, the cylinder pressure can be measured before the test, and then at a sufficiently long time after the test to allow the cylinder to warm to its initial temperature. The test is started by first closing the shutoff valve (without adjusting the metering valve) and then opening the cylinder valve. The shutoff valve is then opened and a stopwatch started. The injection should continue until a steady down-hole pressure is obtained. A sample field sheet for conducting the test is shown in Figure 5.

c. **Calculations**

The air permeability can be calculated using a dimensionless parameter $W(u)_{ss}$ defined as:

$$W(u)_{ss} = \frac{\Delta p \; 4\pi \; k \; \rho \; b}{\mu \; Q_m} \tag{5}$$

Δp = steady state pressure change (M/Lt^2),
k = air permeability (L^2),
ρ = air density (M/L^3),
b = length of the test interval (L),
μ = air dynamic viscosity (M/Lt),
Q_m = air-flow rate (M/t).

The value of $W(u)_{ss}$ depends on depth below land surface of the test interval and the depth to the water table (or lower no-flow boundary). The relationship between flow rate, pressure change, and permeability also depends on the borehole radius. The graph shown in Figure 6 can be used to estimate a value of $W(u)_{ss}$ multiplied by a borehole-radius factor, r_f, for the test interval and water table depths appropriate for a given test. The borehole-radius factor, r_f, can be computed using the following formula

$$r_f = \frac{1}{1.3259 \; r_{well}^{-0.4855}} \tag{6}$$

where

r_{well} = borehole radius in meters.

Once the borehole-radius factor has been computed, $W(u)_{ss}$ can be computed as follows:

AIR-PERMEABILITY MEASURES

Well # ______________________ Date ______________________

Operator(s) ____

Tank pressure before injection ________________

date and time of measurement ____________ air temp ____________

Tank pressure after injection ________________

date and time of measurement ____________ air temp ____________

---

	transducer	pressure gage
Borehole pres. prior to injection	units ________	units ________
	________	________

Time injection started ____________ Flow meter reading ____________

Time injection ended ____________

Manual Measurements (used as a backup only)

Pressure units ____________

TIME	PRESSURE	TIME	PRESSURE

Figure 5. Sample Field Sheet for Conducting *In Situ* Permeability Test.

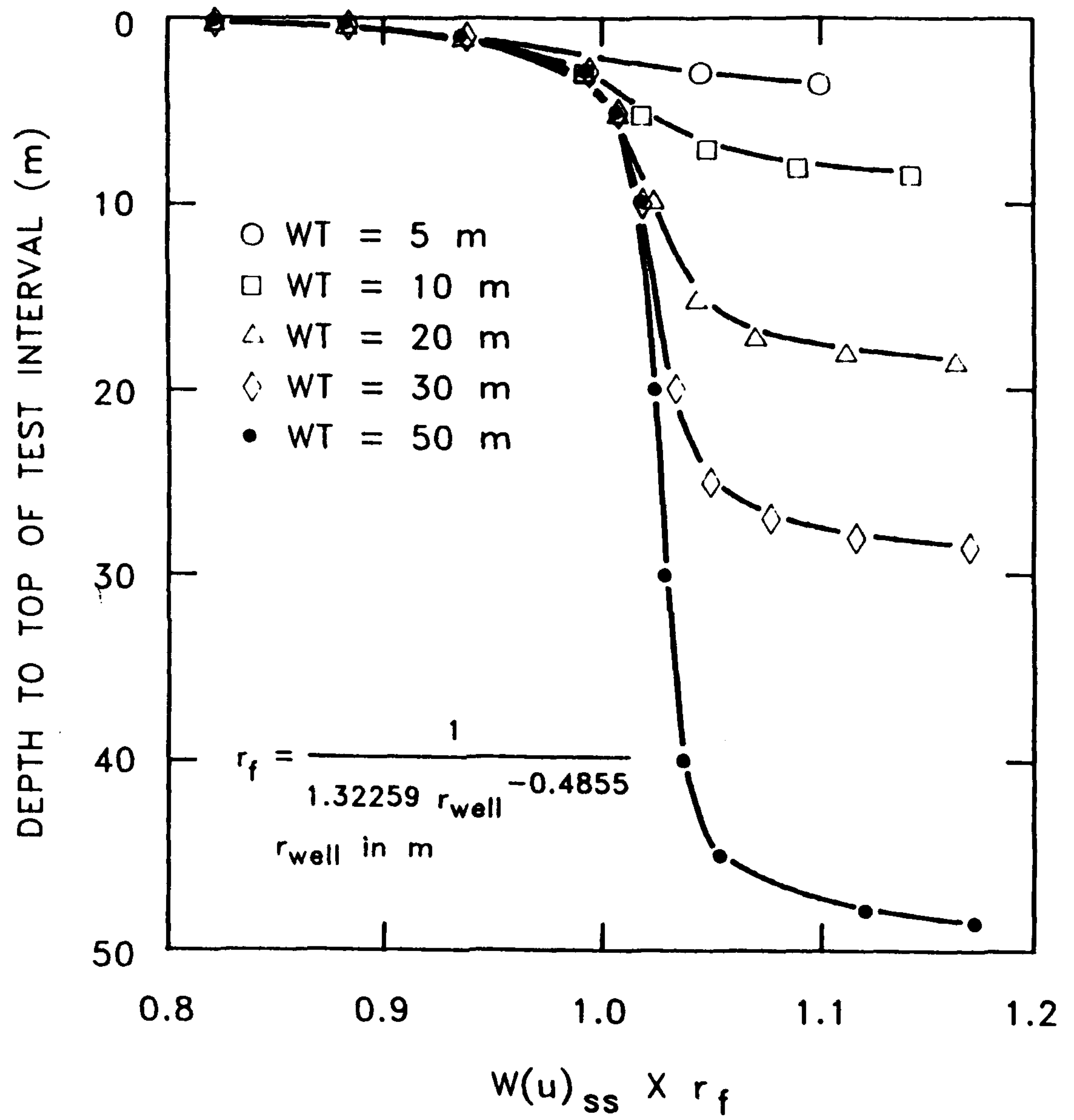


Figure 6. Plot of $[W(u)_{ss} \times r_f]$ Versus Depth of Test Interval for Several Depths to the Water Table.

$$W(u)_{ss} = \frac{\textit{value from graph}}{r_f} \quad (7)$$

The air permeability is then given by

$$k = \frac{\mu \; Q_m \; W(u)_{ss}}{\Delta p \; 4\pi \; \rho \; b} \quad (8)$$

The mass air-flow rate (Q_m) can be computed from the cylinder pressure data as

$$Q_m = \frac{V \; m \; \Delta p_{cylinder}}{R \; T \; \Delta t} \quad (9)$$

where,

V	=	cylinder volume (L^3)
m	=	molecular weight of injection gas (M/mole)
$\Delta p_{cylinder}$	=	change in cylinder pressure over length of test
R	=	gas constant (M L^2/mole K t^2)
T	=	absolute temperature of cylinder gas (K)
Δt	=	elapsed injection time (t).

Equation (9) assumes that the cylinder pressure measurements were made at the same temperature. If the injection gas is nitrogen, the pressure measurements are in Pascals, cylinder volume is in cubic meters, and elapsed time is in seconds, Equation 9 reduces to:

$$Q_m = \frac{0.0033692 \; \Delta p_{cylinder} \; V}{T \; \Delta t} \quad (10)$$

where Q_m is in kg/second.

Cylinder volumes can generally be obtained from distributors. A standard "*Q*" size high-pressure cylinder has a nominal volume of 0.0438 cubic meters.

As previously mentioned, parameters such as the mass air-flow rate (Q_m) or the length of the test interval can be computed by estimating an air permeability value and rearranging Equation 8. The dimensionless graph can also be used to conduct air permeability tests on existing monitoring wells provided that the down-hole pressure at the top of the open or screened interval can be accurately measured.

SECTION IV

CONCEPTUAL DESIGN

A conceptual design is useful for providing a more realistic estimate of the cost and time required for site cleanup to be used in the decision process, and it provides a starting point for the pilot- or full-scale system design. A conceptual design need not take a long time to prepare nor be complicated; in fact, because of the limited information available at most sites and the uncertainties in the site characteristics and the projection of system behavior, a simple design process is likely to provide as good an estimate as a more complicated technique.

The following steps are suggested for conceptual design:

- Collect necessary information.
- Define general vent layout.
- Determine total air volume required for cleanup.
- Set either cleanup schedule or flow rate.
- Derive relationship between time required, flow rate, number of operating vents, and estimated vacuum required.
- Determine reasonable design parameters.

Descriptions of each of these steps, including examples taken from the Hill AFB demonstration, comprise the remainder of this section.

A. NECESSARY INFORMATION

The information necessary to prepare a reasonable conceptual design are:

- General site characteristics (see Section II.A)
- Nature of contaminants
- Total spill mass
- Distribution of contamination (depth and area)
- Air permeability of soil (see Section II.A.3.a)
- Borehole logs (see Section III.B.1.d)
- Knowledge of air emissions regulations governing the application

Not all of the above information may be known very accurately, nor may it be possible to acquire such data. For instance, in many situations the total spill mass cannot be estimated by any means except soil sample analysis. Because of heterogeneities in the soil, the spill mass estimated by this method may be in great error. The uncertainties involved in the input variables to the conceptual design (and later, to the detailed design) must be kept in mind when evaluating remediation options.

B. GENERAL VENT LAYOUT

To determine the general vent layout, the contaminant distribution, the subsurface features, and the limitations on the placement of equipment and vents must be considered. It should also be determined whether such options as groundwater wells (for aquifer decontamination) or nested vents screened in different depth intervals (for stratified soils) are necessary.

The type of vents should also be specified. Horizontal vents placed in trenches are better for shallow spills, whereas vertical vent wells are used for deeper contamination. The simplified developments below are for conceptual design of a system containing vertical or horizontal vents.

C. ESTIMATE OF AIR VOLUME NECESSARY FOR CLEANUP

This section provides means of estimating the total amount of air which must be extracted from the soil for removal of a given fraction of the contaminants. Two methods are presented; (1) an equilibrium estimate and (2) an adjusted equilibrium estimate. An equilibrium estimate was shown to be reasonably accurate in application to the Hill AFB demonstration results. The adjusted equilibrium value is used to account for non-idealities in field situations and uncertainties in site data. Each value should be calculated to provide a range of possible requirements.

1. Equilibrium Estimate

Assumptions made in estimating air volume required for cleanup are (1) there is perfect contact of air with contaminants; (2) the contaminants are distributed evenly in the soil; and (3) equilibrium exists at each point in the soil. Under these assumptions, the entire spill volume may be considered to be in contact with the entire air flow. Using equilibrium relationships and the average contaminant composition and concentration, an estimate of the total amount of air needed for removal may be found.

Two equilibrium relationships in common use are Henry's Law and Raoult's Law. Henry's Law may be written as

$$Y_i = H_i c_i \tag{11}$$

where Y_i is vapor concentration of component i, c_i is liquid concentration of component i, and H_i is the Henry's Law constant for the compound at the temperature of interest. The Henry's Law constant for many compounds may be found in the literature expressed in a variety of units. Henry's

Law is usually applied when the contaminants are dissolved in water at concentrations in the parts-per-million range. This could correspond, for example, to a relatively insignificant spill quantity or to a spill that was dispersed over a large soil volume.

Raoult's Law may be written as

$$y_i P = x_i P_i^{sat} \tag{12}$$

where y_i is vapor phase mole fraction of component i, P is the total pressure, x_i is the liquid phase mole fraction of component i, and P_i^{sat} is the vapor pressure of component i at the temperature of interest. Raoult's Law describes the vapor-liquid equilibrium existing with an ideal mixture of volatile compounds. It is more applicable to situations where the contaminants form a phase separate from the water present in the soil. This would correspond, for example, to a spill of a large quantity of material or to a spill that is concentrated in a small volume of soil.

AWARE, Inc. (Reference 17) and Wilson et al. (Reference 37) have published calculations of models based upon Henry's Law, mainly for chlorinated organics. Marley and Hoag (Reference 38) and Johnson et al. (Reference 2) have presented models based on Raoult's Law, with application to fuel hydrocarbons.

For the purpose of modeling removal of fuel hydrocarbons, in particular JP-4, Raoult's Law should be more applicable in most cases. A very simple equilibrium model for removal calculations based upon Raoult's Law is presented in Appendix B. The results of this model using a representative JP-4 standard composition and soil temperatures of 50, 55, and 60°F are shown in Figure 7. Because of the equilibrium assumptions made in the derivation of the model, the results are presented in scaled form and may be used for the conceptual design of a system of any size. The results are plotted as percent of spill removed versus the removal factor, *RF*, which is the amount of air contacted in liters of air at standard conditions per gram of JP-4 in the initial spill. By selecting a desired mass removal, the amount of air needed per gram of JP-4 may be estimated. The total amount of air contacting the contaminants necessary for removal is then calculated by multiplying this value by an estimate for the total mass of the spill, or,

$$V_{tot} = M \cdot RF(\text{from graph}) \quad , \tag{13}$$

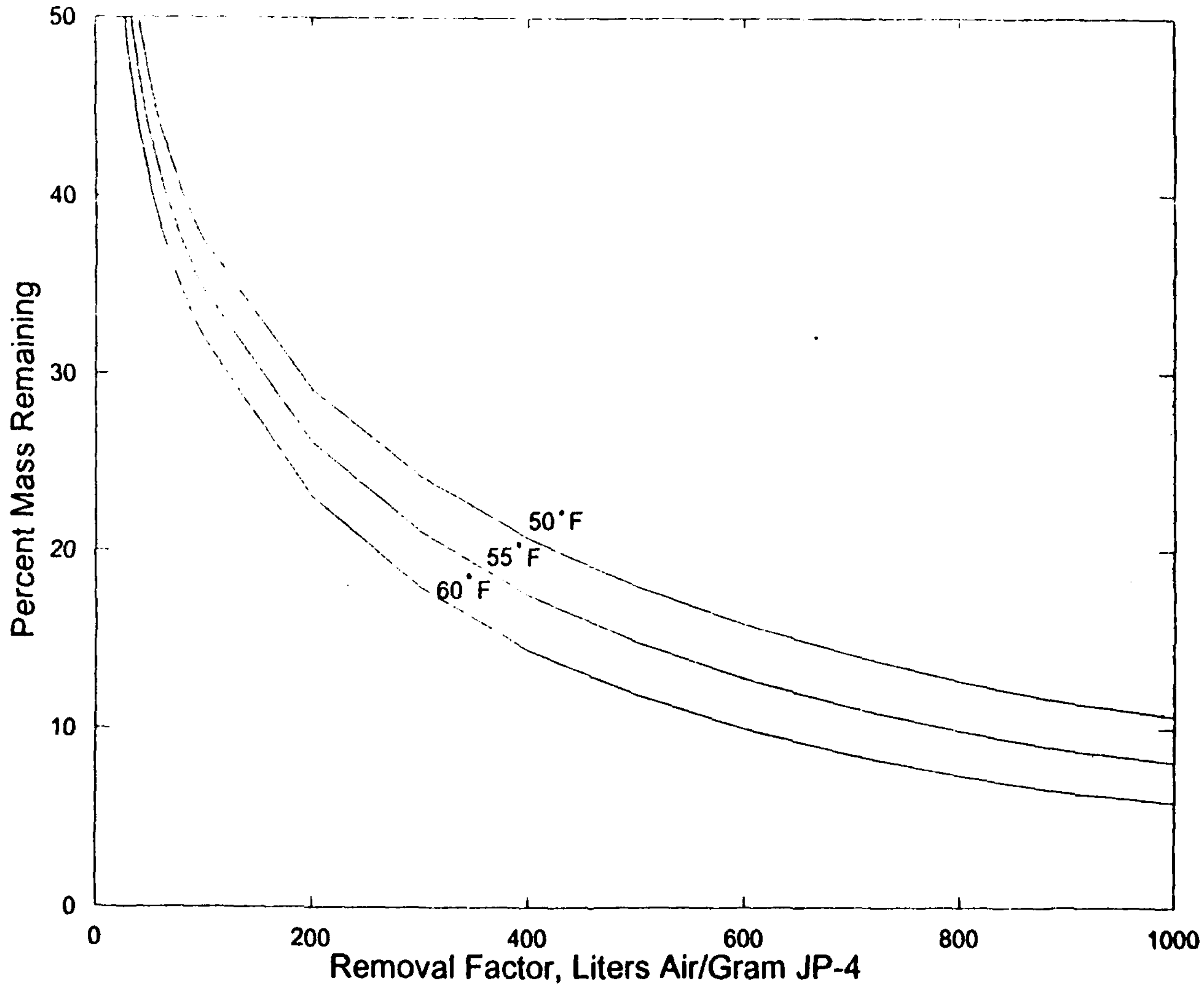


Figure 7. Scaled Removal Curves for a JP-4 Standard Composition Derived from Raoult's Law Equilibrium Model.

where V_{tot} is the total amount of air contacted in liters at standard conditions and M is the total spill mass in grams. (JP-4 has a density of approximately 800 grams/liter, or 3,025 grams/gallon. To convert liters of air to cubic feet, divide by 28.32.)

For spills other than JP-4 or for other temperatures, curves such as the one in Figure 7 may be derived using a model such as that described in Appendix B, with input of the contaminant composition and temperature. Johnson et al. (References 1 and 2) have presented similar curves for gasoline removal derived from a slightly more complex model.

Example Assume that 80 percent removal of a 26,000-gallon JP-4 spill in 55°F soil by volatilization is desired. This is a reasonable design removal value for JP-4 for two reasons. First, JP-4 contains heavy fractions, difficult to remove by volatilization. These heavy fractions are less likely to be transported in the soil and therefore pose less of a hazard than some of the more volatile and mobile compounds such as benzene. Secondly, biodegradation is likely to aid in the removal of the hydrocarbons, including the heavy fractions. Biodegradation rates during the Hill AFB soil venting demonstration were 15-20 percent of the volatilization rate. It is expected that other sites will probably provide conditions for bioactivity similar to or more favorable than those of Hill AFB.

The data in Figure 7 show that about 320 liters of air/gram JP-4 are required for removal of 80 percent of the initial spill mass. For a 26,000 gallon (7.07×10^7 gram) spill, at least 2.5×10^{10} liters of air, or 8.9×10^8 cubic feet of air will be required for removal.

2. Adjusted Equilibrium Estimate

In the absence of biodegradation or other removal mechanisms, the removal factor *RF*, found in the previous section, will provide the most optimistic estimate for the desired mass removal. The reasons for this are based upon the idealizations of the model, which assumed that there is perfect contact of the entire residual spill mass with the entire subsurface air flow. In real situations, non-ideal contact is more likely, particularly in cases of more complex geohydrology or free product layers on the water table. Therefore, it is possible that a greater air volume than that predicted in the previous section will be required (of course, it is also possible that biodegradation will cause much greater removal rates and, thus, require less air volume).

For the purposes of budget and schedule, a realistic upper bound on the required air volume is needed. Two techniques may be used for finding an upper estimate for the removal factor. One technique which would require no site data (and therefore less connected with reality) is the

assumption of a heavier hydrocarbon composition than the JP-4 standard used in the generation of Figure 7. Another technique would require an estimate of the venting efficiency, which could be best determined from a pilot test. Both methods are outlined in the following sections.

a. Air Volume Estimate from Heavier Hydrocarbon Distribution

Figure 8 presents the results of equilibrium removal calculations performed with the input of a hydrocarbon composition derived from a subset of soil samples taken at Hill AFB. The mass removal curve for this mixture, which exhibits slower removal rates by volatilization than the JP-4 standard, may represent removal of a "weathered" JP-4 by volatilization. This curve could be used in place of Figure 7 in estimating the upper-limit estimate for the total amount of air required for cleanup.

<u>Example</u> For the "weathered" JP-4, a removal factor of RF=890 liters/gram corresponds to 80 percent mass removal by volatilization at a soil temperature of 55°F (see Figure 8). For the purpose of deriving an upper bound for removal, this value is rounded up to 1,000 liters/gram. In the case of the 26,000-gallon (7.07 x 10^7 gram) JP-4 spill, an upper estimate for the amount of air required would be,

$$V_{tot} = \left(1000 \frac{\text{liters of air}}{\text{g JP-4}}\right)(7.07 x 10^7 \ g) = 7.07 x 10^{10} \ liters = 2.8 x 10^9 \ ft^3 \ . \tag{14}$$

b. Air Volume Estimate from Venting Efficiency

This technique is more likely to give realistic values for required air volume; however, it requires a value for venting efficiency which must either be estimated or preferably derived from a pilot study [see Section V; in particular, Equation (31)]. The venting efficiency is the ratio of the amount of air needed to achieve a given mass removal as predicted by equilibrium relations to the actual amount of air required. Therefore, an adjusted removal factor may be calculated by

$$RF_{adj} = \frac{RF \text{ (from equilibrium removal curve)}}{Eff} \ , \tag{15}$$

where RF_{adj} is the removal factor adjusted for nonequilibrium conditions and Eff is the fractional venting efficiency. The total amount of air required would then be calculated by

$$V_{tot} = M(RF_{adj}). \tag{16}$$

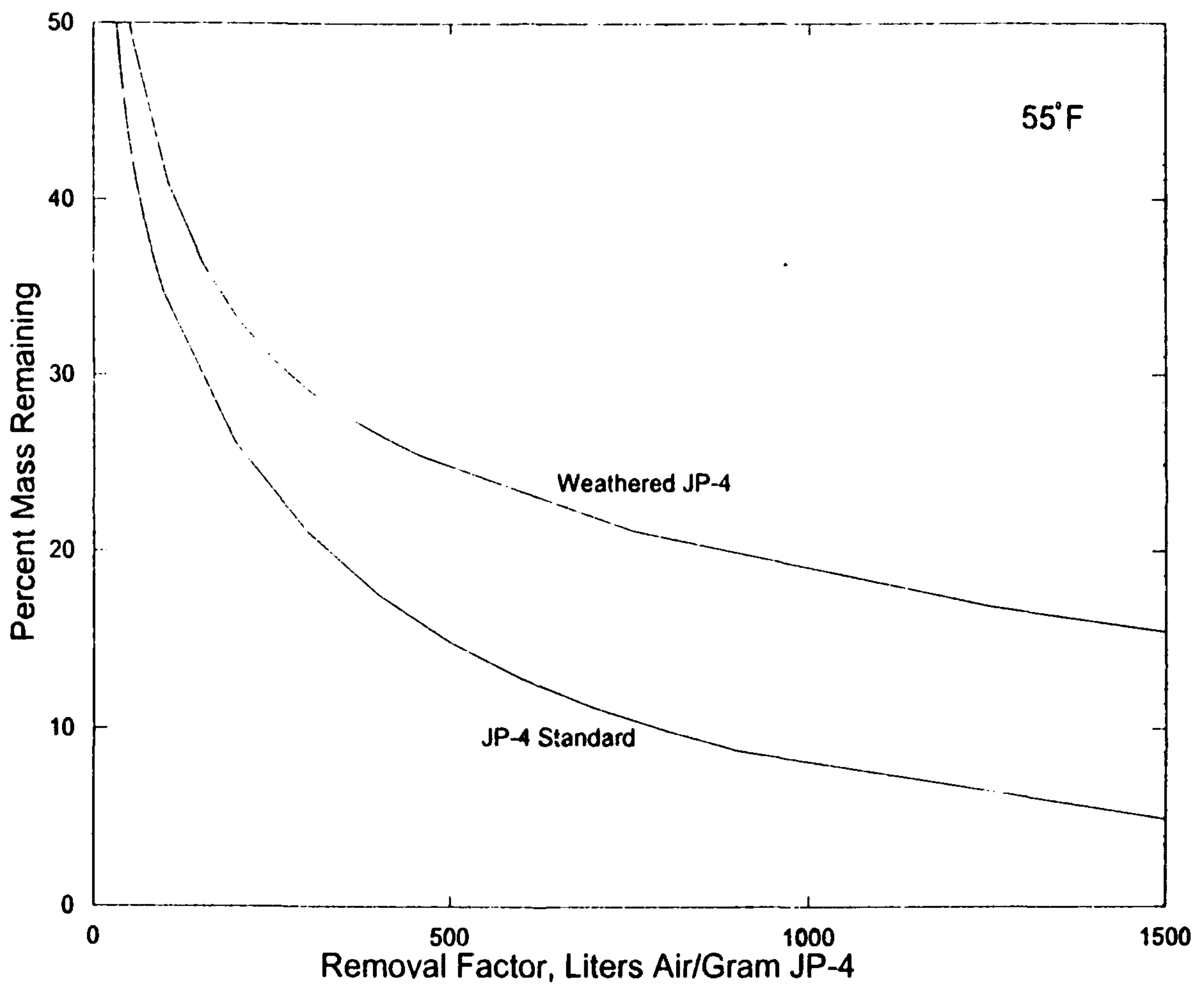


Figure 8. Scaled Removal Curves for a "Weathered" JP-4 and a Standard JP-4.

Example The Hill AFB demonstration system exhibited nearly ideal equilibrium behavior, corresponding to a venting efficiency approaching 1.0. Therefore, RF_{adj} would be nearly equal to $\dot{R}F$. However, if the system were considerably different, such as a spill existing mainly as a free product layer on the water table, a much lower efficiency would be expected. Johnson et al. (Reference 2) mathematically derived a venting efficiency of 8 percent for a sample case. If the 26,000-gallon-JP-4 spill were assumed to be in this configuration, the adjusted removal factor would be

$$RF_{adj} = \frac{320 \frac{liters\,of\,air}{g\ JP\text{-}4}}{0.08} = 4000 \frac{\text{liters of air}}{\text{g JP-4}} \tag{17}$$

and an estimate of the total amount of air required for 80 percent mass removal by volatilization would be

$$V_{tot} = 7.87 x 10^7 g \left(4000 \frac{\text{liters of air}}{\text{g JP-4}} \right) = 3.15 x 10^{11}\ liters = 1.1 x 10^{10}\ ft^3 \ . \tag{18}$$

It is noted that a much larger air volume is required in this nonideal example.

D. SETTING THE CLEANUP SCHEDULE AND EXTRACTION FLOW RATE

The relationship of the cleanup schedule and air flow rate to the total amount of air required for cleanup is simple:

$$V_{tot} = Qt \tag{19}$$

where V_{tot} is the total air volume required, Q is the total volumetric extraction air flow rate, and t is time. Either Q or t must be specified and values for V_{tot} were found in the previous sections. The flow rate, Q, would be specified in such cases as when a blower or emissions control device of a given flow capacity is available at a site, or if such equipment is available in only certain sizes. Time, t, would be specified if there was a time limit for cleanup of the site.

Example For the 26,000-gallon JP-4 spill, estimates for V_{tot} of 8.9 x 10^8 and 2.8 x 10^9 cubic feet were made from equilibrium and adjusted equilibrium relations, respectively. If there is a cleanup goal of 1 year to reach the point corresponding to 80 percent removal by volatilization, then estimates for the required flow rate would be,

$$Q = \frac{V_{tot}}{t} = \left\{ \begin{array}{c} \dfrac{8.9x10^8 \ (ft)^3}{5.26x10^5 \ \min} = 1690 \ scfm = 0.8 \quad std.m^3/s \quad (equil.-eq.13) \\ \\ \text{or} \\ \\ \dfrac{2.8x10^9 \ (ft)^3}{5.26x10^5 \min} = 5330 \ scfm = 2.5 \ std.m^3/s \quad (adj.-eq.14) \end{array} \right\} \qquad (20)$$

Alternatively, if the design is to be centered around an available emissions control device with a 1500 standard cubic feet/minute flow capacity, then the estimated times required for cleanup would be,

$$t = \frac{V_{tot}}{Q} = \left\{ \begin{array}{c} \dfrac{8.9x10^8 \ ft^3}{1500 \ scfm} = 5.33x10^5 \ \min = 1.1 \ yr \quad (equil.-eq.13) \\ \\ \text{or} \\ \\ \dfrac{2.8x10^9 \ ft^3}{1500 \ scfm} = 1.67x10^6 \ \min = 3.6 \ yr \quad (adj.-eq.14) \end{array} \right\} \qquad (21)$$

E. VACUUM REQUIREMENTS

The amount of time necessary for cleanup may be decreased by increasing the extraction flow rate. Increasing the flow rate comes with a price, however, since the vacuum required to pull the air from the vents will increase as well. This will lead to higher power requirements and more costly blower designs. The equations presented in this section will allow one to estimate the vacuum required for various design schemes. From this information, a region of reasonable operation (based upon values for vacuum, number of vents, time, and flow rate) may be determined for a particular case, from which estimates of cost and schedule may be made.

The assumptions made in the simplified approach in deriving the design equations are:

- Homogeneous contaminant distribution
- Homogeneous soil properties
- Raoult's Law equilibrium governing removal
- One-dimensional radially symmetric flow toward extraction vent
- No multiple-vent effects upon air flow distribution

Derivations of the design equations are presented in Appendix C.

1. **Vertical Vents**

a. **Estimation of the Vacuum Required for Vertical Vent, Radial Flow Case**

The one-dimensional radial flow case is shown in Figure 9. The air extraction rate from the vent, assuming compressible ideal gas flow, may be expressed as (Reference 39)

$$q = \frac{\pi k h (P_{atm}^2 - P_v^2)}{\mu P_v \ln\left[\frac{r_{atm}}{r_v}\right]} , \tag{22}$$

where q is the extraction flow rate at the conditions of the vent ($q=Q/N$, where N is the number of operating vents), k is the air permeability of the soil, P_{atm} is the absolute atmospheric pressure, P_v is the absolute pressure in the extraction vent, h is the length of the slotted section of the vent, μ is the viscosity of the air, r_v is the radius of the vent, and r_{atm} is the minimum radial distance from the center of the vent to the point where the pressure is essentially atmospheric.

In cases in which it is not possible to acquire the information necessary to evaluate the equations presented in the next section (such as cases in which contaminant mass is poorly defined), Equation (22) could be used to estimate the vacuum/flow rate relation for a given vent geometry in a particular soil type. In order to determine P_v, an estimate of $\ln(r_{atm}/r_v)$ must be made. Values presented by Johnson et al (Reference 2) and measured at Hill AFB indicate that, in most cases, $\ln(r_{atm}/r_v)$ should range from about 3.5 (least permeable) to 6.5 (most permeable). A value of 5 for this term may provide reasonable order-of-magnitude estimates for vacuum requirements.

b. **Vacuum Required for Contaminant Removal**

Combination of Equation (22) with contaminant removal relationships results in the following design equation for the vacuum required, DP, for contaminant removal (see Appendix C for derivation and assumptions):

$$DP = P_{atm} - P_v = P_{atm} - \left(P_{atm}^2 - \frac{C_{av} \mu P_{atm} (RF) A \ln\left[\frac{2}{r_v}\left(\frac{A}{N\pi}\right)^{1/2}\right]}{\pi N k t} \right)^{1/2} . \tag{23}$$

For a given case, P_{atm}, C_{av}, μ, RF, A, and r_v may be specified. Therefore, Equation (23) may be used to investigate the relationship of vacuum requirements to number of vents and the time required for cleanup.

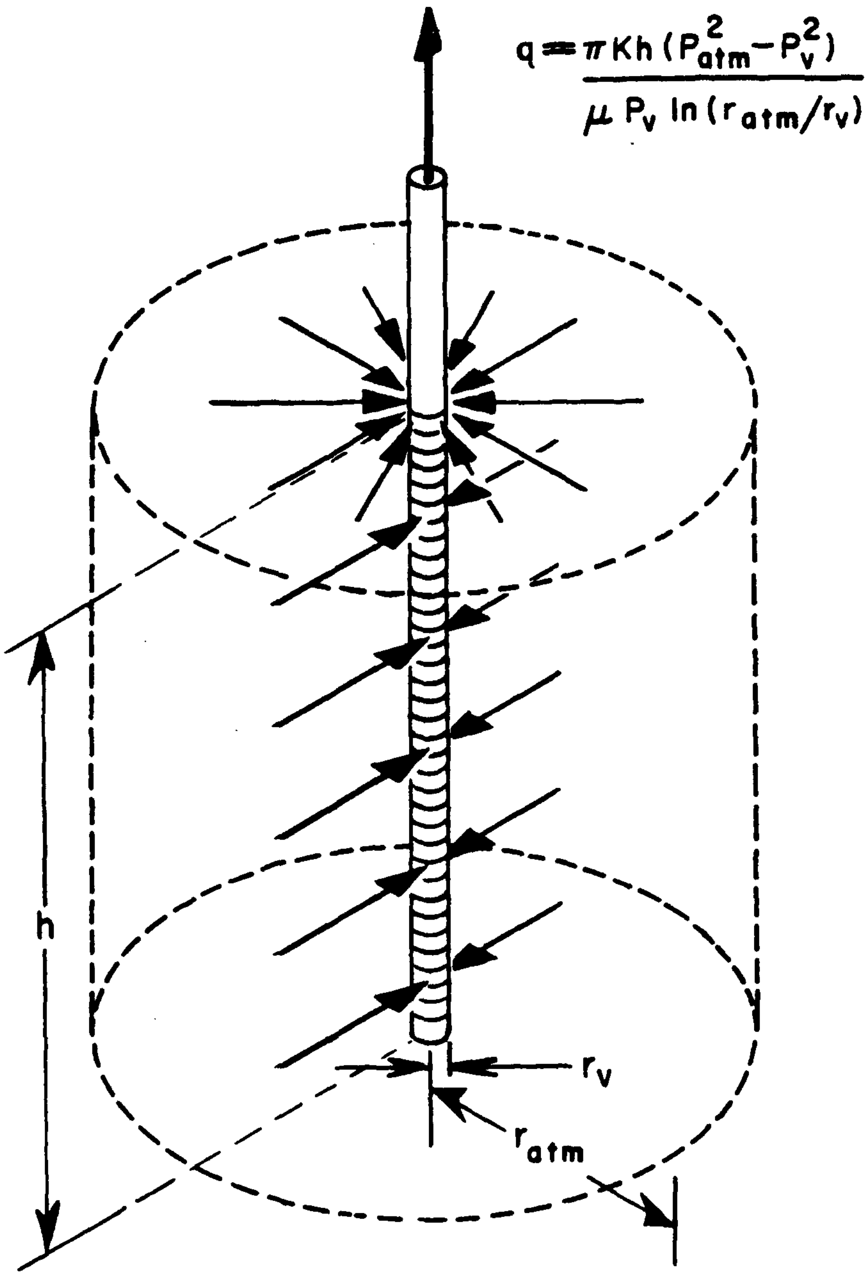


Figure 9. One-Dimensional Radial Flow Case Used for Conceptual Design for a Vertical Well.

Setting the total flow rate and time for cleanup defines the relationship of N and DP. If Q is too high (or t too short), then DP will be unreasonably high for any realistic number of vents. A design sequence will therefore involve generation of vacuum curves corresponding to different integer values of N. This may be done by input of N into Equation (23) and generation of a curve for DP versus t from this equation. This process is then repeated with a new set of values for Q and t. It is possible to achieve the same cleanup in a short time with a large flow rate, either with many vents at moderate vacuum and flow at each vent, or with fewer vents and higher vacuum and flow at each vent. It also is possible to achieve cleanup over a long period with much lower flows and vacuum requirements. The values from several of these curves generated by Equation (23) must then be considered, weighing the higher capital costs for more vents versus higher capital and operating costs for blowers of higher vacuum and/or volume capacity and higher capital costs of emissions control equipment of higher capacity. Also, the political and environmental costs accrued by longer restoration times must be factored into this portion of the design.

In this evaluation, N is the number of operating vents. It is likely that in an application some of the vents will not be operated at particular times. In these cases, the total number of vents installed will not be equal to N; rather, N is an estimate of minimum amount of vents that must be operated at the total flow rate Q to remain below a vacuum requirement of DP and achieve the cleanup in a desired amount of time. The total number actually installed will be based on engineering judgment of the situation, regarding contaminant distribution and soil properties, and for most cases will be considerably greater than N.

Example As an illustration of this step in the conceptual design, consider the example of the 26,000-gallon JP-4 spill. For this case it will be assumed that the vents have a radius of 4 inches (0.1 meter) and a screened section length of 40 feet (12.2 meters), the air permeability of the soil to be 2.8×10^{-7} cm^2 (2.8×10^{-11} m^2), and the area of contamination to be 125 x 100 feet = 12,500 ft^2 (1,160 m^2). With a contaminant depth of 50 feet (15.2 meters), the contaminant volume is 625,000 ft^3 (17,680 m^3), and the average contaminant concentration in the soil is 7.87×10^7 grams JP-4/17,680 m^3 = 4,450 grams/m^3. To produce an upper estimate of the vacuum requirements, we will choose the RF to be 1,000 liters of air/gram of JP-4 (1.0 m^3/gram). We will consider the air to be at 55°F and 1 atm, so that μ=0.044 pound/feet hour (1.82×10^{-5} Pa·s). With these values, Equation (23) becomes,

$$DP = 101{,}325\,Pa - \left((101{,}325\,Pa)^2 - \frac{(4{,}450\,g/m^3)(1.82x10^{-5}\,Pa \cdot s)(101{,}325\,Pa)(1.0\,m^3/g)(1{,}160\,m^2) \ln\left[\frac{2}{0.1\,m}\sqrt{\frac{1160\,m^2}{N\pi}}\right]}{N\pi(2.8x10^{-11}\,m^2)t} \right)^{1/2} . \qquad (24)$$

Simplifying,

$$DP = 101{,}325\,Pa - \left(1.027x10^{10}\,Pa^2 - \frac{3.43x10^9 \ln\left[\frac{384}{\sqrt{N}}\right] Pa^2 \cdot yr}{Nt} \right)^{1/2} . \qquad (25)$$

For a cleanup time of 1 year, this results in a vacuum requirement of 304 inches of water (75,650 Pascals) for two operating vents, 150 inches of water (37,300 Pascals) for three vents, and 102 inches of water (25,400 Pascals) for four vents (it is not possible to achieve high enough flow from a single vent for cleanup in this time period).

Unless the site cleanup was of high priority, it would likely be better to operate with a longer time scale. It would then be possible to operate at a lower flow rate with lower vacuum requirements. Remember also that this estimate is for vacuum at the vent, and pressure drops in the piping system must be added to this value to determine blower capabilities. Selection of a value of t=3.2 year (Q=1,500 ft^3/minute) results in vacuum requirements of 156 inches of water (38,940 Pascals) for a single operating vent, 65 inches of water (16,080 Pascals) for two vents, 40 inches of water (10,000 Pascals) for three vents, and 29 inches of water (7,190 Pascals) for four operating vents.

Curves for various total flow rates (and estimated cleanup times) for this example using the adjusted removal factor are shown in Figure 10. As can be seen, shorter lengths of time and smaller numbers of operating vents cause larger vacuum requirements. If possible, it is desirable to design a system with vacuum requirements less than about 100 inches of water, since less expensive blowers and lower operating costs would be required than at higher vacuum levels due to increased power requirements at the higher vacuum levels. Also, higher vacuum levels will cause increased water table rise, possibly bringing groundwater in contact with contaminated zones. In general, if emissions control is required, the number of vents will not be a major factor in the cost of the system; therefore, the addition of more vents than the minimum is urged.

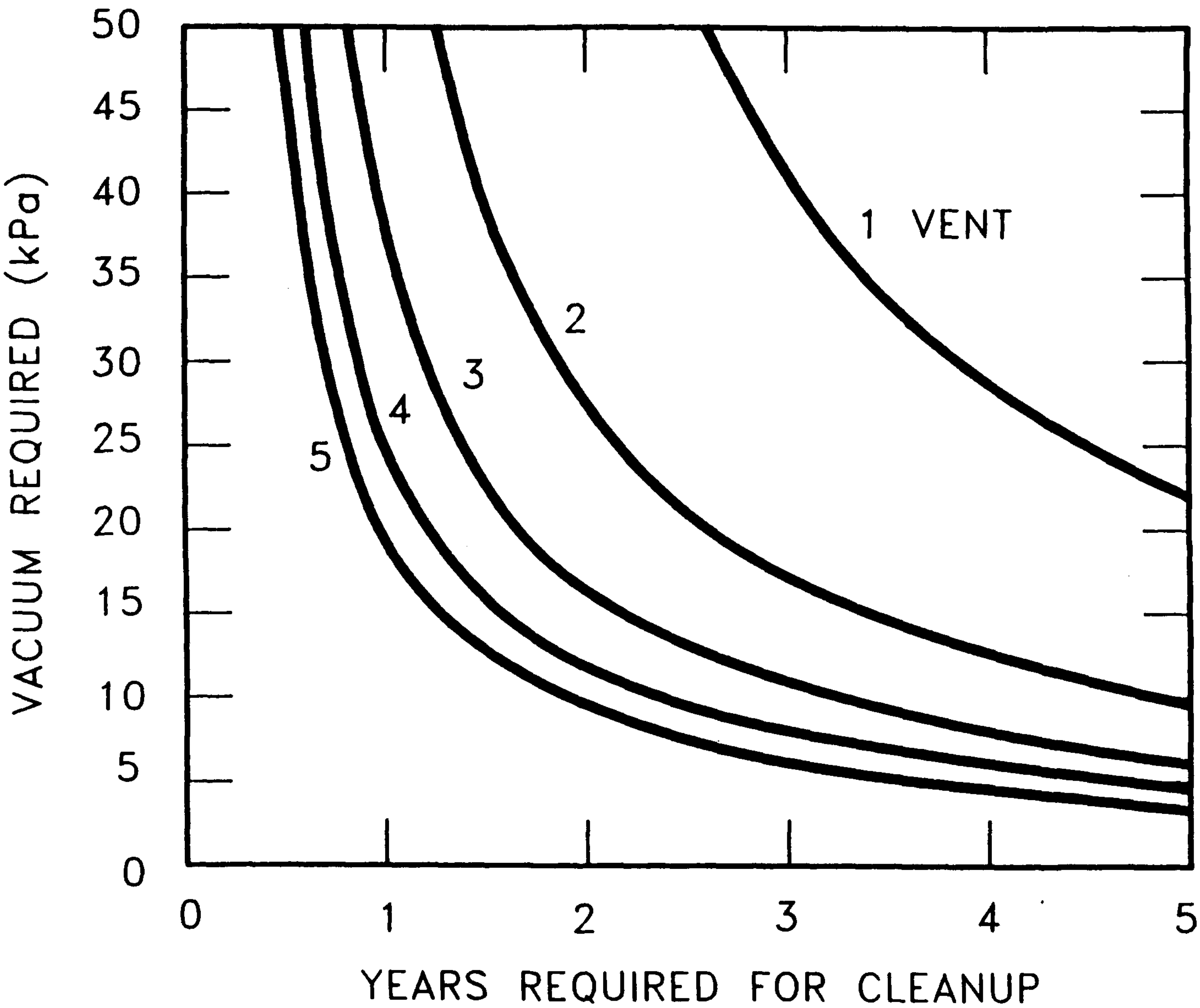


Figure 10. Vacuum Requirements for Conceptual Design Example Case.

Definition of the reasonable area of operation will depend on the blowers available, their power consumption curves, and the need of expediency in remediation. A reasonable region of operation may be defined for this case with time = 1 to 3 years, and blower capabilities of 20 to 100 inches of water vacuum. This will require at least from one to four operating vents. In actuality, the system that was installed at this site (the Hill AFB demonstration system) included 15 vertical vents, of which at least two were operated at a maximum total flow rate of 1,200 standard cubic feet per minute. Two rotary lobe blowers rated at 1500 standard cubic feet per minute total extraction rate (t=3.4 years) and vacuum capability of 100 inches of water vacuum were specified. The lower flow rates achieved were the result of pressure corrections due to altitude and the slip curves of the blowers. Actual data from the site includes 20 inches of water required for extraction of 250 ft^3/minute from one vent [Equation (24) yields 19.6 inches of water] and 28 inches of water for 830 standard cubic feet per minute [Equation (24) yields 31 inches] from two distant vents. Agreement between prediction and observation for these cases is quite good. As operating vents are brought closer together so that radii of influence overlap, vacuum requirements become greater than expected. For two vents closer together than their depth, 62 inches of water was actually required for total extraction of 690 standard ft^3/minute, whereas Equation (24) yielded 26 inches.

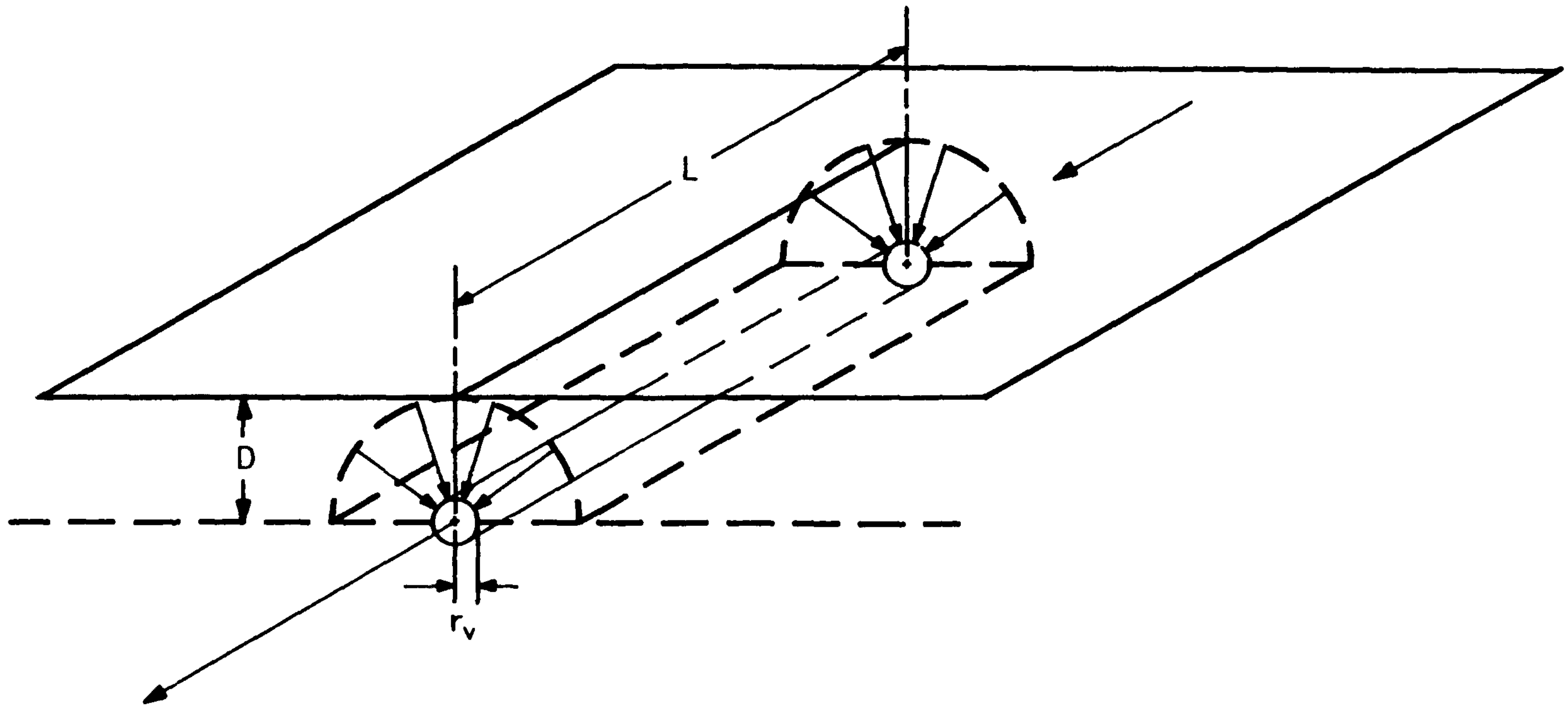
2. Horizontal Vents

The model system assumed for radial flow toward a horizontal vent is shown in Figure 11. The air extraction rate from the vent, assuming compressible ideal gas flow, may be approximated as,

$$q = \frac{\pi k L (P_{atm}^2 - P_v^2)}{2 \mu P_v \ln\left[\frac{D}{r_v}\right]} \tag{26}$$

where q is the extraction flow rate at the conditions of the vent ($q=Q/N$, where N is the number of operating vents), k is the air permeability of the soil, P_{atm} is the absolute atmospheric pressure, P_v is the pressure in the extraction vent, L is the length of the slotted section of the vent, μ is the viscosity of the air, D is the depth of the extraction vent, and r_v is the radius of the vent.

Combination of Equation (26) with equilibrium contaminant removal relationships results in the following design equation (see Appendix C):



$$q = \frac{\pi k L \left(P_{atm}^2 - P_v^2\right)}{2 \mu P_v \ln\left(\frac{D}{r_v}\right)}$$

Figure 11. One-Dimensional Radial Flow Case Used for Conceptual Design for a Horizontal Well.

$$DP = P_{atm} - P_v = P_{atm} - \left(P_{atm}^2 - \frac{C_{av} D^2 \mu P_{atm} RF \ln\left[\frac{D}{r_v}\right]}{kt} \right)^{1/2} \quad . \tag{27}$$

In this case, there is no explicit dependence of vacuum requirements on the number of vents; the minimum number of vents is set by geometric considerations as described in the paragraphs below. The only variable likely to be adjusted in a particular application to achieve a more favorable vacuum requirement is t, which is linked directly to flow rate by Equation (19). The depth of the vents is not considered variable for a given contaminant distribution.

b. Horizontal Vent Spacing

For the vents described above to achieve the desired cleanup goal at vacuum levels on the order of the value predicted by Equation (27), the maximum distance between vents must be

$$\text{vent spacing} = \frac{W}{N} = \frac{\pi D}{2} \tag{28}$$

where W is the width of the assumed rectangular contaminated soil volume having length L and depth D.

Horizontal vents should be placed no farther apart than about 1.5 times their depth. Depending on the cost of installation, it is probably preferable to place vents closer than the maximum spacing to allow flexibility of operation and to ensure adequate treatment of all soil zones.

SECTION V

PILOT TEST

Pilot tests are valuable for two major reasons: (1) actual field data may be collected for use in design of full-scale systems and (2) an operating system may be placed in the field quickly, performing some of the remediation concurrent with full-scale system design and construction. This latter point is important in that pilot systems may be placed into operation to determine the feasibility of venting or to test a particular venting design without the cost of failure of a full-scale system. Also, this provides the freedom of a scale-up of operation such as described in Reference 8.

Several vendors use single-vent or multiple-vent systems to collect site-specific design data. Pilot test systems for collection of data for expansion or for full-scale design should include more equipment than just a vent, blowers, and emissions control device (if necessary). The systems should include extracted gas analyzers and pressure monitoring points in the soil at various depths and distances from the extraction vent. The vapor concentration measurements provide some data that may be used for rough prediction of removal performance and emissions control requirements, while the pressure monitoring data allow calculation of air permeabilities for equipment selection and vent placement. The pressure monitoring also provides information on the homogeneity of the site and the effects of subsurface features.

A. PILOT TEST DESIGN

The major points which must be decided upon when planning a pilot test include the following:

- Length of test
- Equipment selection
- Monitoring Equipment
- Vent construction and placement

Each of these points will be discussed in the paragraphs below.

1. Length of Test

The first step in planning a pilot test is determining what data will be collected from the test. Such a decision will dictate both schedule and equipment selection. If the test is to be performed only to investigate the air permeability of the soil and to measure the initial concentration of the extracted gas, a few extraction tests at various flow rates until steady state pressures are achieved will suffice. Such a set of tests would last only a few days operating time, and emissions would probably be low enough that emissions control would not be necessary. If a pilot test is to be used for

prediction of the schedule for site cleanup, longer operating times, possibly 2 weeks to 2 months, would be required. Emissions control would be more likely for this longer operating time. A pilot test could also be operated to collect the above data, then run for an indefinite period afterward until the system was expanded into a full-scale operation. In such a case, the pilot system would be designed to operate as a small remediation system, with emissions control likely. Communications with the appropriate regulatory agencies is urged well in advance of the planned pilot test to determine the need for emissions control and to expedite permitting.

2. Equipment Selection

A schematic of equipment included in a generic soil venting pilot test is shown in Figure 12. The equipment which must be selected for inclusion in a pilot test system will be a v uum blower, motor speed control (optional), well screen and riser pipe, pressure monitoring point m als, piping and valves, demister, and emissions control system (if necessary). Selection of these items will depend mainly upon size, materials of construction, and safety concerns. In the following, important elements of equipment selection for a pilot test are outlined; further helpful information may be found in Section VI, Implementation.

a. Sizing

The size of each piece of equipment will depend on the gas flow rate and/or the vacuum requirement used for the design. As a starting point for the design flow rate, use a flow rate per vent in the reasonable operating range as defined in the conceptual design of Section IV. Corresponding to this flow rate per vent will be an estimated vacuum requirement [see Equations (22), (23) or (27)]. For flexibility in operation, it is recommended that the conceptual design estimates for vacuum and flow rate be multiplied by a factor of 1.5 to 2 or greater for design values.

b. Blower

Using the vacuum and flow rate design values, a vacuum blower or blower package (including blower, motor, and silencers) may be specified. Due to the high hydrocarbon concentrations likely to be encountered in a pilot test, it is recommended that the blower be constructed with spark-resistant internals and coupled with an explosion-proof motor.

c. Piping and Vents

Well screen, riser pipe, pressure monitoring points, piping, and valving will most likely be constructed of plastic (PVC is most common) unless regulations require the use of metal screen and riser pipe for the vents and monitoring wells. Viton valve seats are suitable for use with fuel hydrocarbons. Pressure monitoring points may be constructed of any convenient size, whereas the

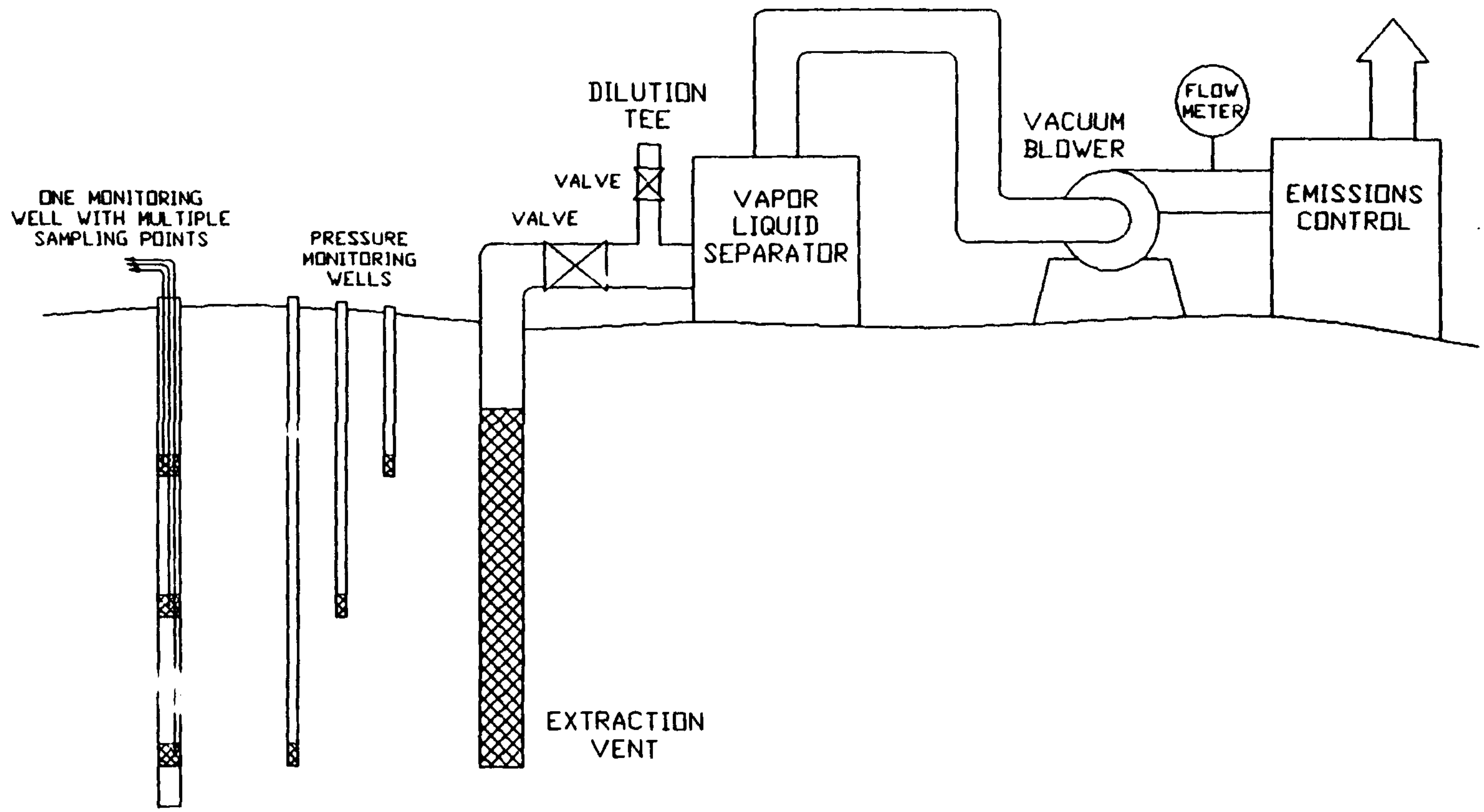


Figure 12. Schematic for a General Soil Venting Test.

piping carrying gas flow must be sized to minimize pressure drops. Table 6 lists suggested piping sizes for various flow rates. The table listings show the maximum flow rate a given size pipe may contain for an estimated pressure drop of approximately 10 inches of water per 100 feet of straight pipe.

TABLE 6. PIPING SIZE VS AIR FLOW RATE

Nominal Pipe Size In Inches, (cm)	Suggested Maximum Air Flow Rate Standard Cubic Feet Per Minute, (Standard Cubic Meters Per Second)
1 (2.54)	20 (0.0094)
2 (5.08)	100 (0.0472)
3 (7.62)	250 (0.118)
4 (10.2)	500 (0.[illegible]36)
6 (15.2)	1350 (0.638)

d. Vapor-Liquid Separator

A vapor-liquid separator (knock-out drum) may consist of a drum which is equipped with an air inlet and an outlet, a mesh or chevron mist eliminator, a liquid level gauge, a liquid removal tap, and a vacuum relief valve. Such a separator is shown in Figure 13. A vapor-liquid separator suitable for flows up to about 500 standard ft^3/minute and vacuum levels up to 100 to 150 inches of water may be constructed from a 55-gallon drum with a demister mesh pad and inlet and outlet connections attached to the drum cover. A vacuum relief valve may be simply constructed by a vertical pipe leg run from a bucket of water next to the drum, to the desired water column height for release, and down to a connection on the drum. When excessive vacuum levels occur which could damage the drum, the water is pulled through the pipe into the drum, draining the bucket and allowing atmospheric air into the system. The vacuum relief valve may double as a vacuum gauge if transparent pipe is used.

e. Emissions Control

The amount of hydrocarbons extracted must be estimated to determine if emissions control is necessary for the pilot plant. An estimate may be made by assuming that the concentration in the extracted gas will remain at the levels measured in soil gas samples taken prior to venting. This

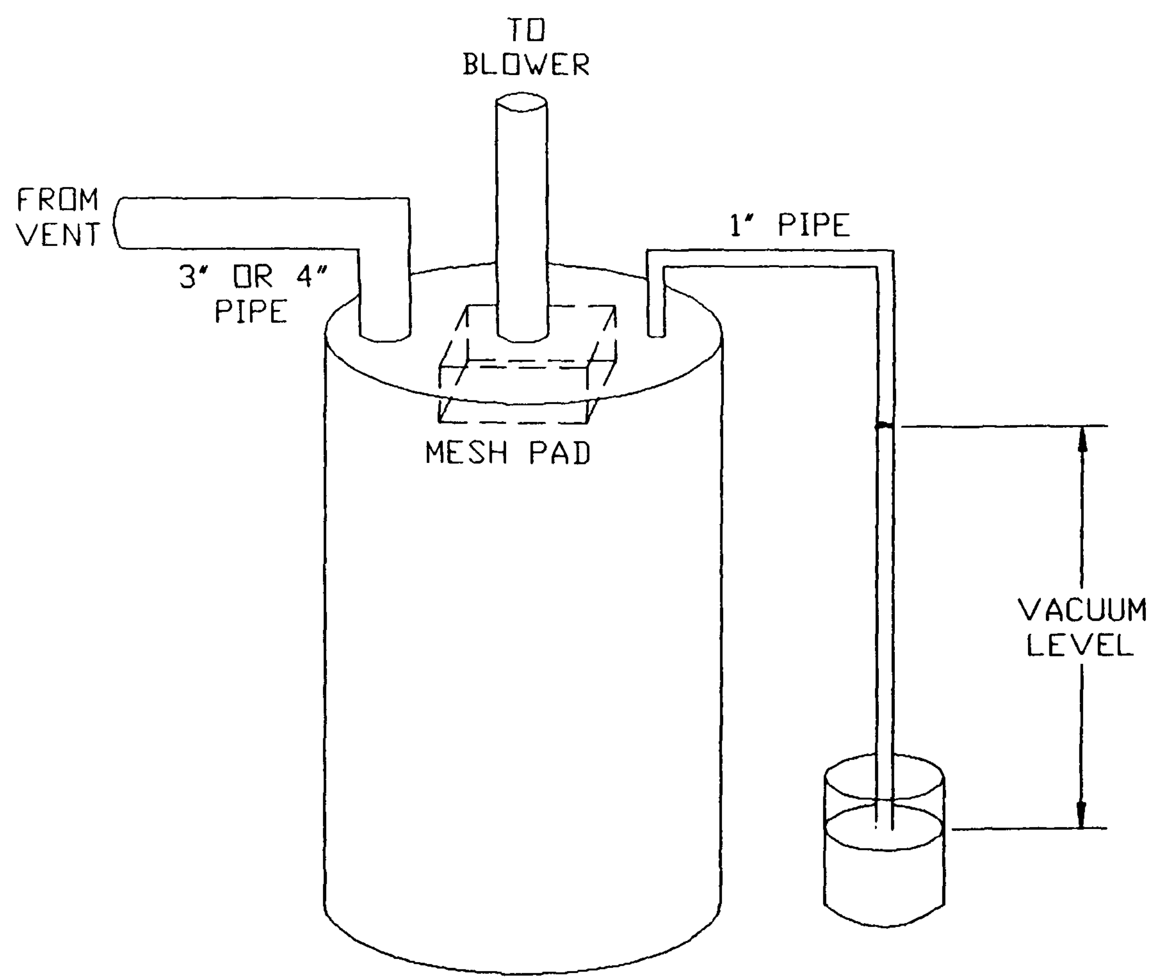


Figure 13. Vapor Liquid Separator.

assumption will provide a conservative estimate of the hydrocarbon removed since the extracted gas concentration will actually decrease with time during ISSV operations. The total amount of hydrocarbons extracted would then be calculated by multiplying the concentration by the total volume of gas at standard conditions that will be extracted over the course of the planned tests. This amount, as well as the expected maximum concentration and duration of the test, should be reported to the appropriate regulatory agency for the determination of the need for emissions control or limitations upon test duration and discharge.

The gas stream to be treated by emissions control during a pilot test is likely to be of high concentration and of low to moderate flow rate. Carbon adsorption, using prepackaged 55-gallon drums, is an attractive option due to the ease of implementation. However, carbon usage is likely to be high because of the high concentrations. The carbon must be disposed of or regenerated, so other alternatives should be considered. Condensation could be used to lower the hydrocarbon load to a carbon unit. Condensation would be quite attractive and easily implemented if the pilot system is operated during winter months. Flaring (or thermal oxidation) is possible with proper safety controls. Emissions control, such as catalytic oxidation units, requiring greater capital investment and more involved installation, could be included if the pilot system is to be run for an extended period.

3. Monitoring Equipment

Three types of monitoring equipment are necessary for a pilot test:

- Gas analyzers
- Flowmeters
- Pressure monitoring devices

a. Gas Analyzers

Gas analyzers could be used to monitor the contents of the extracted gas, gas pulled from pressure monitoring points, and effluent from the emissions control device.

Hydrocarbon analyzers are needed for determination of concentration and composition of hydrocarbons in the gas. Total hydrocarbon analyzers containing a flame ionization detector (FID) or a photoionization detector (PID) would be useful for continuously measuring total hydrocarbon concentration of the gas stream. A gas chromatograph would be useful for measuring both the total hydrocarbon concentration and the concentration of several hydrocarbon components in grab samples. Selection of the proper monitors for a particular application may depend upon regulatory approval.

Analyzers for measuring the carbon dioxide and oxygen content of gas samples may be used for observing bioactivity induced by aeration of the soil. Measurement of oxygen and carbon dioxide levels in gas pulled from pressure monitoring points will also allow tracking of the progress of oxygen infiltration toward the extraction vent, providing a means of observing flow paths and residence times for gas in the soil. Several portable oxygen analyzers readable in the range 0 to 25 percent are available. Gas sampling kits using sampling tubes (e.g., Draeger tubes) may be used for sensitive measurement of carbon dioxide levels. Tubes, to cover the range of a few hundred parts per million to 20 percent, are available.

b. Flowmeters

Flowmeters are essential for determining the amount of air extracted during the pilot test. As described in Section VI, orifice meters are likely the easiest to employ accurately in a pilot test. If multiple vents are employed, it may be suitable to include one orifice meter for determination of total extraction flow rate. An insertion-type velocity meter, such as a pitot tube, could be used for measuring relative flows from individual vents.

c. Pressure Monitoring Devices

Vacuum gauges are needed for pressure monitoring at the vent and the pressure monitoring points, and differential pressure gauges are necessary for determination of flow rate at orifice meters or pitot tubes. It is usually not necessary to have costly pressure transducers connected to a data acquisition system for a pilot test, since steady state readings should provide suitable information. Differential pressure gauges such as Magnehelic gauges are available in several convenient ranges and may be used for measuring both differential and vacuum readings. U-tube manometers may be constructed simply and inexpensively, and will yield adequate results if the density of the filling fluid is known accurately.

4. Vent and Pressure Monitoring Points

The vent or vents installed for the pilot test should be designed as closely as possible to the vent design to be used in the full-scale test. Vent design details to be considered include the choice of vertical or horizontal placement, the depth of the vent (preferably to or below the furthest depth of known soil contamination), the length of the screened interval of the vent (preferably to include all depths of known soil contamination), the vent pipe diameter (suitable for the flow rates to be attained), and the auger hole size for vertical vents (suitably sized to fit vent pipe through hollow stem).

The single vent or one of multiple vents should be placed as near as possible to the center of the known contaminated soil zone. This placement is aimed at providing the best geometry for air-contaminant contact and thus high gas concentration and contaminant removal rate. Central placement should provide estimates of soil properties which are most characteristic of the site. A centrally-located vent is also likely to be operated for a relatively long period during the course of the remediation. Other positions for additional vents should be chosen in areas of differing or questionable soil structure or contamination.

Pressure monitoring points should be placed at several depths and distances from the vent or vents. The number of these will be limi'ed by cost. It may be less costly to place several pressure monitoring probes at different depths in a single borehole, separated by bentonite and grout. This configuration may be prone to error if proper seals are not formed between probes, allowing air flow to bypass along the edges of the grout plugs.

The placement of the pressure monitoring probes will be influenced by knowledge of the soil at the site. For sites of simple geohydrology, probes placed at three or four depths and three or four distances from the extraction vent should be suitable. In such cases, the depths should be distributed throughout the depth of the vent. Additional vents below the depth of the extraction vent may be added if air flow from below is possible. For stratified sites, at least one pressure probe in each stratum is recommended. Other depth positions to be considered for placement would be above or below discontinuities, such as directly above a groundwater surface or clay layer.

The radial distance of the pressure monitoring points may be set by estimating the radial variation of vacuum under assumed conditions. Assuming one-dimensional radial flow, the pressure distribution in the soil may be estimated as [see Equation (22)],

$$P(r) = P_v \left(1 + \frac{\left(\left(\frac{P_{atm}}{P_v} \right)^2 - 1 \right) \ln\left[\frac{r}{r_v} \right]}{\ln\left[\frac{r_{atm}}{r_v} \right]} \right)^{1/2} \tag{29}$$

with

$$P_v = \frac{\left(\left(\mu q \ln\left[\frac{r_{atm}}{r_v}\right]\right)^2 + (2\pi hkP_{atm})^2\right)^{1/2} - \mu q \ln\left[\frac{r_{atm}}{r_v}\right]}{2\pi hk} \tag{30}$$

where $P(r)$ is the absolute pressure in the soil at a distance r from the center of the extraction vent, P_v is the absolute pressure at the extraction vent having a radius r_v, r_{atm} is the radius at which the absolute pressure is essentially equal to the atmospheric pressure P_{atm}, h is the screened interval length of the vent, k is the air permeability of the soil, μ is the viscosity of the gas, and q is the total volumetric gas extraction rate. In order to estimate the variation of pressure with radius, $P(r)$, an estimate of $\ln(r_{atm}/r_v)$ must be made. As stated in Section IV, in most cases $\ln(r_{atm}/r_v)$ should range from about 3.5 (least permeable) to 6.5 (most permeable). A value of 5 may provide reasonable order-of-magnitude estimates for vacuum requirements.

The above equations may be simply implemented in a spreadsheet with input of the vent geometry parameters, h and r_v, the constants μ and P_{atm}, and estimates for k and $\ln(r_{atm}/r_v)$. The pressure at a radial distance may then be estimated as a function of flow rate and radial distance.

The pressure monitoring points should be placed with regard to the results of the pressure versus distance calculations at the planned flow rates. The location of the farthest monitoring point from the extraction vent should be such that the vacuum to be induced at that point at the lowest planned flow rate is greater than the lowest reliable reading achievable for the pressure gauges to be used. If the probe is placed at a greater distance from the extraction vent than this, no reading will be made during the lowest flow rate test. Near the vent, the pressure will vary greatly as a function of distance; thus, it would appear that this would be a prime area for many probes. However, the design is limited by the accuracy of placement of the probes and the effect of probes upon the flow field close to the vent. It is recommended that the closest probes, if placed in vertical boreholes, be at a distance no less than 5 feet from the extraction vent. Between the closest and farthest pressure monitoring probes, the remaining probes should be distributed to give a reasonable variation in reading between points at all of the planned flow rates.

An example of the above approach may be illustrated using data from the Hill AFB demonstration. For this test, pressure monitoring points were placed at three radial distances, and extraction flow rates ranging from 0.029 to 0.094 m^3/second were to be used. *In situ* permeability test results produced an average of 3×10^{-11} m^2 for the air permeability of the soil. The vent borehole

radius was 0.102 meters and the vent screened interval was 12.2 meters. Gas viscosity was estimated at 1.82 x 10^{-5} Pascal seconds, and atmospheric pressure was 90018 Pascals at the Hill AFB altitude.

Because the sandy soil at Hill AFB was known to be quite permeable, the above equations were evaluated for values of $\ln(r_{atm}/r_v)$ of 5 and 6.5 for the lower and upper flow rates, as shown in Figure 14. In these plots, predictions of vacuum induced in the soil as a function of radial distance are compared to actual test readings. The predictions are dependent upon the $\ln(r_{atm}/r_v)$ value chosen, and thus are not expected to provide very accurate pressure profiles; moreover, the predictive equation assumes that air flow from the surface is negligible. While this assumption is valid for deep vents or where an impermeable surface barrier is used, air flow from the surface may cause substantial deviations in other situations. These effects are discussed in more detail in Section V.C.2. However, the curves appear to provide reasonable order-of-magnitude values for pressure monitoring point placement and pressure gauge selection.

A conservative approach to placement would be to select a minimum measurable vacuum level, e.g., 100 Pascals, and place the outermost probe at a radial distance no greater than that predicted by the lower curve for the lowest flow rate at the 100 Pascal level. With this approach, probes would be placed no farther out than about 10 meters. The innermost probe could be placed at 3 meters, and the center probe between them, possibly at 6 meters. For the demonstration, probes were placed at distances of 3.05, 6.1, and 9.15 meters. With probes in these positions, an estimate of the pressure gauge ranges required could be made by selecting the pressure on the lower 0.029 m^3/second curve and the pressure on the higher 0.093 m^3/second curve at each distance. For example, for the innermost probe a vacuum gauge readable in the range of 350 to 2100 Pascals would be specified. Reading ranges of at least 200 to 1700 Pascals and 125 to 1400 Pascals would be needed for the remaining two probes.

B. PILOT TEST OPERATION

A pilot test may be designed to obtain the following information:

- Air permeability of soil
- Vacuum requirements
- Subsurface air flow patterns
- Variation of extracted gas concentration and composition
- Venting efficiency
- Other supporting information

Methods for obtaining the above information are described in the following:

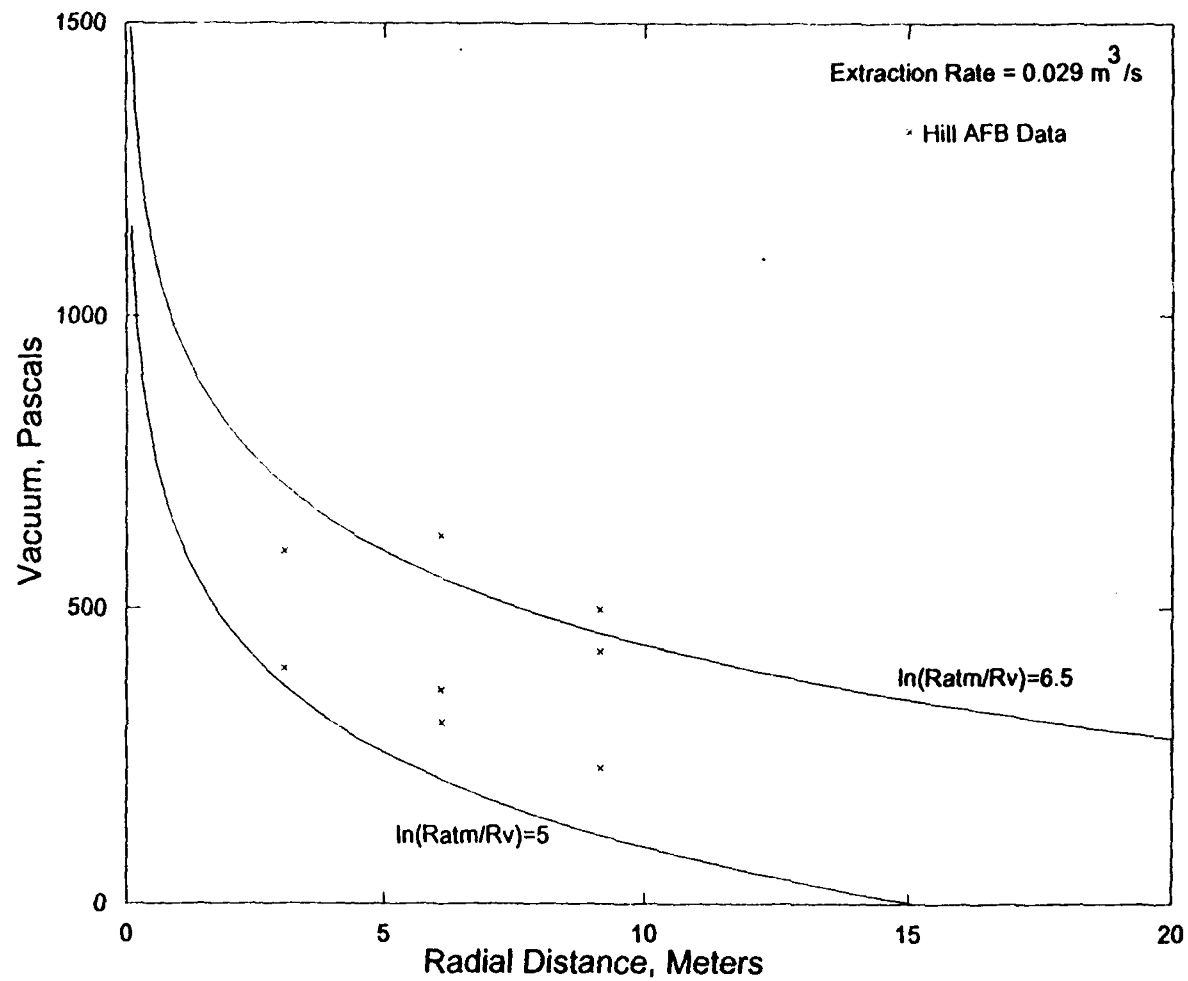


Figure 14. Example Pilot Test Vacuum Predictions.

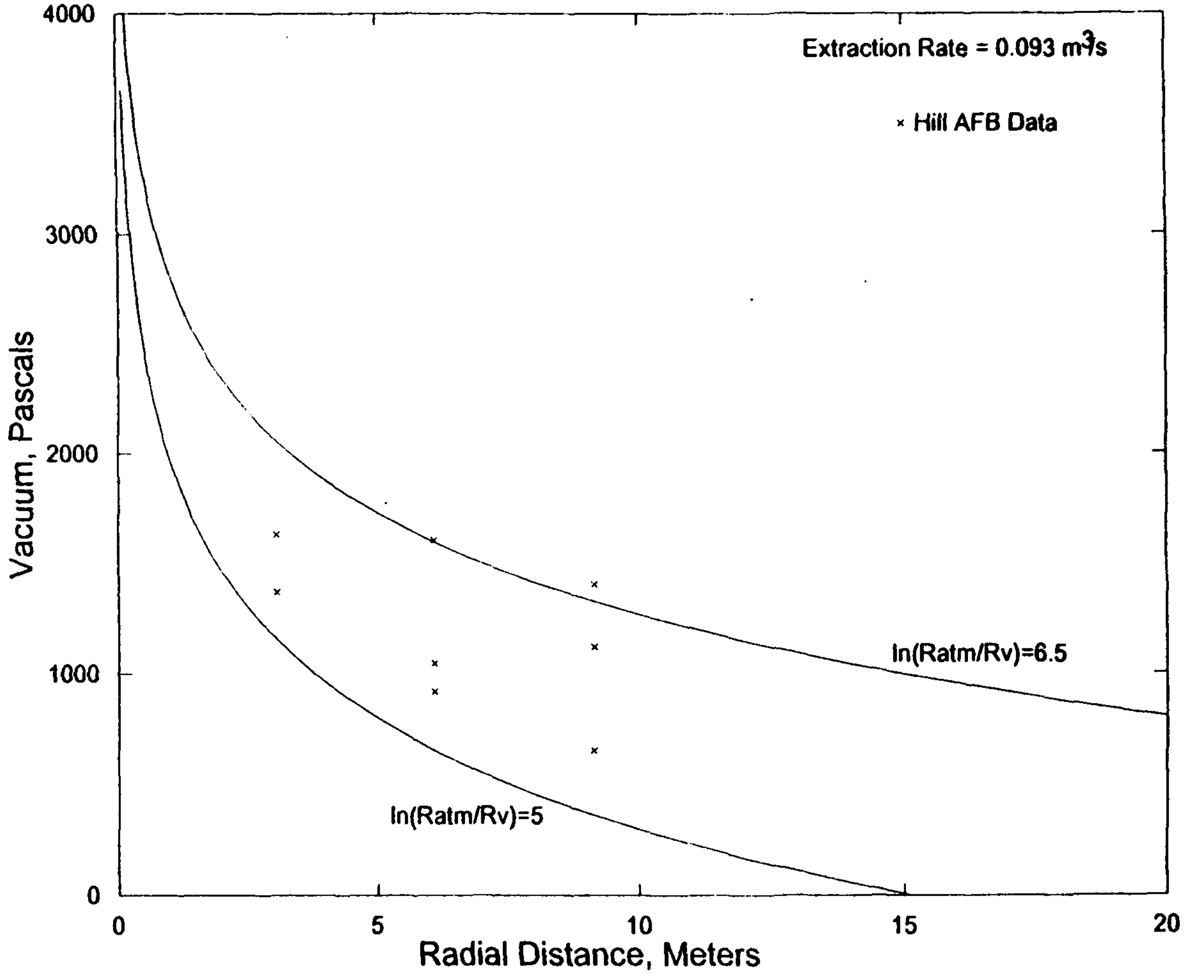


Figure 14. Example Pilot Test Vacuum Predictions (Concluded).

1. **Flow Information**

The first three items of information above may be obtained by conducting a series of extraction tests at different flow rates. The system may be operated either with a speed control on the blower motor or a dilution tee at the blower inlet to vary the rate of gas extraction. Operation is continued until steady state is reached in the flow field as evidenced by unchanging vacuum readings at all pressure monitoring points. Vacuum readings from all points will allow estimation of the air permeability of the soil, as will be described in Section V.C.1. By plotting the vacuum readings on a contour diagram, the paths of streamlines, showing the course of air flow through the soil, may be estimated. By conducting the tests at several different flow rates, the curve for single-vent vacuum requirements may be determined.

2. **Variation of Extracted Gas Concentration and Composition**

Data needed to provide this information are collected using the gas analyzers. Concentration and composition measurements should be taken periodically and recorded as a function of time. The flow rate should also be monitored to allow development of the relationship between concentration and the amount of gas extracted.

3. **Venting Efficiency**

An empirically-derived venting efficiency, suggested by Johnson et al. (Reference 2), is one way to account for nonidealities in system behavior when predicting removal performance. Venting efficiency could be estimated by performing one or a series of shutdown tests. Prior to the start of a shutdown test, the extracted gas concentration must be allowed to drop considerably below the initial concentration.

The time to begin the shutdown period could be set by constraints on either the allowable time of operation or contaminant discharge, or could be set as the point at which the difference between the initial concentration and the measured concentration is greater than an established multiple of the level of uncertainty in concentration measurement.

The shutdown period is necessary for reequilibration of soil gas with the contaminants in the soil. For more permeable soils, the period may be as short as a day, whereas for less permeable soils or for cases with soil heterogeneities, a longer period may be required. To determine the point at which equilibrium has been reached, samples of gas could be periodically extracted from the vent and analyzed. Once the gas concentration had steadied, the reequilibration period would be complete. Periodic gas samples from the pressure monitoring points during the shutdown period could also be analyzed to monitor the carbon dioxide buildup and oxygen depletion for evaluation of bioactivity.

Upon restart of the system, preferably at the same flow rate, the concentration in the extracted gas should be noted. If it is quite near the concentration measured before the shut-down period, it may be said that equilibrium controls removal during that portion of venting operations. If the extracted gas concentration upon restart is much higher than that immediately before the shut-down period, diffusion plays a role in contaminant removal.

An estimate of the venting efficiency may be made by considering that the concentration after shutdown is an approximation to the concentration which would be seen if equilibrium controlled removal. Therefore,

$$Eff = \frac{C_1}{C_2} \tag{31}$$

where *Eff* is the fractional venting efficiency, C_1 is the extracted gas concentration prior to shutdown, and C_2 is the extracted gas concentration upon restart. Thus, if $Eff \approx 1$, removal is equilibrium controlled, whereas if *Eff* is less than 1, diffusion is controlling.

It is expected that the venting efficiency will change both with extraction flow rate and with time. Therefore, it would be useful to perform the test at various flow rates; however, if only one test is possible in the schedule, use the highest flow rate practical to provide the lowest estimate possible for venting efficiency. If a long-term pilot test is to be conducted, the venting efficiency should be rechecked as necessary (possibly once per month) to determine if there are significant changes with time.

4. Other Information

Other measurements which may be necessary, depending upon the application, would be water uptake in the extracted gas and water table rise.

If the soil is moist, the rate of water uptake and collection in the vapor-liquid separator could be great. The water collection rate should be noted during the pilot test (as a function of extraction flow rate) to allow design of suitably sized full-scale equipment.

The vacuum induced by the soil venting system will cause the level of the water table to rise locally. This may present problems by causing groundwater contamination by contact with contaminated soil and by excluding soil zones from air flow. If groundwater wells are present in the area, measurements should be made of the water table rise as a function of the applied vacuum. The water level gauge used for the measurements must be designed to provide an airtight seal at the top of the well so as not to allow loss of vacuum, which would cause the water level to fall, producing an erroneous measurement.

C. DETERMINATION OF AIR PERMEABILITY FROM PILOT TEST DATA

A pilot test provides the best data for determining the air permeability of the soil for use in a full-scale system design since the test is very similar to the actual operation of the full-scale system. Pilot test data may be analyzed in at least two ways to determine the air permeability; by application of the one-dimensional radial flow equation and by matching the data with a computer flow model. The first method is less accurate since it is very restrictive in its assumptions; however, it may be quickly and easily applied. Computer modeling, though, may be time-consuming and more costly.

1. Radial Flow

The same equation used for estimation of vacuum requirements for the conceptual design may be used for an approximation of the air permeability from pilot-test data. For this situation, the equation for radial flow for a vertical vent becomes,

$$k = \frac{q \mu P_v \ln\left[\frac{r_p}{r_v}\right]}{\pi h (P_p^2 - P_v^2)} \tag{32}$$

where k is permeability, q is the volumetric extraction flow rate, μ is gas viscosity, P_v is the absolute pressure at the vent, P_p is the absolute pressure at a pressure monitoring point, r_p is the distance from the pressure monitoring point to the vent, r_v is the radius of the vent, and h is the length of the screened section of the vent.

The equation for k may be applied separately to each pressure monitoring point for each extraction flow rate, resulting in a number of different estimates for the air permeability. The values will be meaningful only if the soil is homogeneous. Otherwise, there will be angular and/or vertical variations in permeability. For the homogeneous case, all values may be averaged to produce a reasonable estimate of permeability. If the soil varies in properties, the permeability of each zone may be estimated by making assumptions about the distribution of flow among the zones. An averaged "bulk" air permeability may also be derived, and the relative permeability of different soil zones or strata may be estimated.

An example of this treatment of pilot test data may be presented using the results of the demonstration at Hill AFB, a site with fairly permeable and homogeneous soil. In this test, a vent with a screened interval length of 12.2 meters was operated with an atmospheric pressure of 90018 Pascals and an estimated gas viscosity of 1.82×10^{-5} Pascal-seconds. Pressure monitoring probes were placed at three depths (4.6, 9.15, and 13.7 meters) and three distances (3.05, 6.10, and

9.15 meters) from the extraction vent. The vacuum readings obtained during steady-state extraction during the highest flow rate test (0.094 standard cubic meters per second) and the permeability calculation results are presented in Table 7.

TABLE 7. VACUUM AND PERMEABILITY RESULTS VS DEPTH

Depth (m)	P_v (Pa)	r_p (m)	P_p (Pa)	k (m^2)
4.6	85800	3.05	88649	2.6×10^{-11}
9.15	85800	3.05	88388	2.9×10^{-11}
4.6	85800	6.10	88973	2.8×10^{-11}
9.15	85800	6.10	89100	2.7×10^{-11}
13.7	85800	6.10	88415	3.4×10^{-11}
4.6	85800	9.15	89364	2.8×10^{-11}
9.15	85800	9.15	88898	3.2×10^{-11}
13.7	85800	9.15	88617	3.5×10^{-11}
				Average k = 3.0×10^{-11} m^2

The permeability results at this and other flow rates are quite consistent, even though the pressure monitoring points were spread out in an angular distribution covering 120 degrees of a circle around the extraction vent. This agreement indicates that the soil at the Hill AFB site is quite homogeneous. Also, little variation is seen with depth, as would be expected for one-dimensional radial flow. During the pilot test at Hill AFB, the ground was covered with ice. Thus, the ice layer apparently acted as a surface barrier to produce one-dimensional flow behaviors. An averaged value of 3.0×10^{-11} m^2 (equal to the average of the *in situ* permeability test results) could be used at this site as an estimate of the air permeability of the soil.

2. Modeling

a. Analytic Solution

The one-dimensional model presented above is adequate for design purposes for field situations in which most of the vented air is expected to be drawn laterally to the vent well. These

situations include the presence of a low-permeability soil zone at the surface and the use of an impermeable surface barrier. When most of the vented air enters the vents from the atmosphere, as would be expected for near-surface vents, a one-dimensional model will overestimate the radius of influence of a vent well. In these cases it may be useful to utilize a two-dimensional analytic model to evaluate the likely radius of influence of the vents.

A useful two-dimensional analytic model has been developed which uses the following simplifying assumptions:

- A vent well consisting of a point at a fixed depth, with air withdrawal at a constant rate;
- A uniform layer of soil extending to infinity;
- Upper and lower boundaries which are either no-flow (e.g., impermeable surface barrier, underlying water table) or constant pressure (i.e., atmospheric); and
- The applied vacuum does not exceed 0.1 atmosphere (10133 Pa).

The model is based on Darcy's Law, and solves the flow system using the "method of images" frequently employed in electrostatics. A simple computer program for evaluating the solution to the equations of the model for the radial and vertical components of flow is presented in Appendix D. This program, written in Fortran-77, requires very little computational effort and could be compiled and executed on essentially any personal computer with a Fortran compiler.

b. Numerical models

Models which utilize numerical methods, such as finite elements or finite differences, have been developed to solve the governing partial differential equations which describe air flow in venting applications. One such model, FEMAIR, has been tested using field data from the Hill Air Force Base venting study (Volume III), and was found to describe well the pressure and flow fields.

Use of models such as FEMAIR require substantially greater investment of time, and greater expertise in computer skills, to operate than does the analytical model presented above. The advantage of a numerical model is that because fewer simplifying assumptions are required to reduce the air flow net to a computationally manageable set of equations, far greater flexibility is possible in defining the soil regime. The effects of significant changes in permeability (e. g., the presence of clay or gravel lenses in a silty soil) or nonuniform flow barriers (e. g., the presence of a parking lot or building foundation) on expected air flow patterns can thus be assessed. The amount of data on subsurface hydrogeology typically available at a venting site is not sufficient to warrant application of a highly site-specific numerical model.

Application of FEMAIR has proved useful in evaluating vacuum data in determination of *in situ* permeability, and in producing likely flow patterns resulting from different sets of subsurface conditions and vent configurations (Section VI.A.1). In general, however, numerical flow models are most useful at present in assisting researchers in understanding the factors which control contaminant movement and air flow in the subsurface during the venting process. For design of venting systems, simple one-dimensional (Section V.C.1.) and two-dimensional (Section V.C.2.a.) radial flow models are sufficiently accurate for predicting vent behavior in most venting situations.

c. Comparison of Models

The effectiveness of the image-method analytical model is demonstrated by comparing the results of two basic venting scenarios—flow with and without an impermeable surface barrier--with the results obtained from a simulation developed using the FEMAIR numerical model. A single point-source vent well is set at a depth of 3 meters in a soil layer 15 meters in thickness. The pumping rate is set at 0.1 meter per second and the intrinsic permeability is set at 3×10^{-11} m^2. The solutions for covered and uncovered cases, using the method of images and FEMAIR, are shown in Figure 15. For each case, the flow fields predicted by the two modeling techniques are essentially identical. For the uncovered case, most of the air flow is from the surface downward, resulting in a much smaller radial influence of the well than is simulated for the covered case.

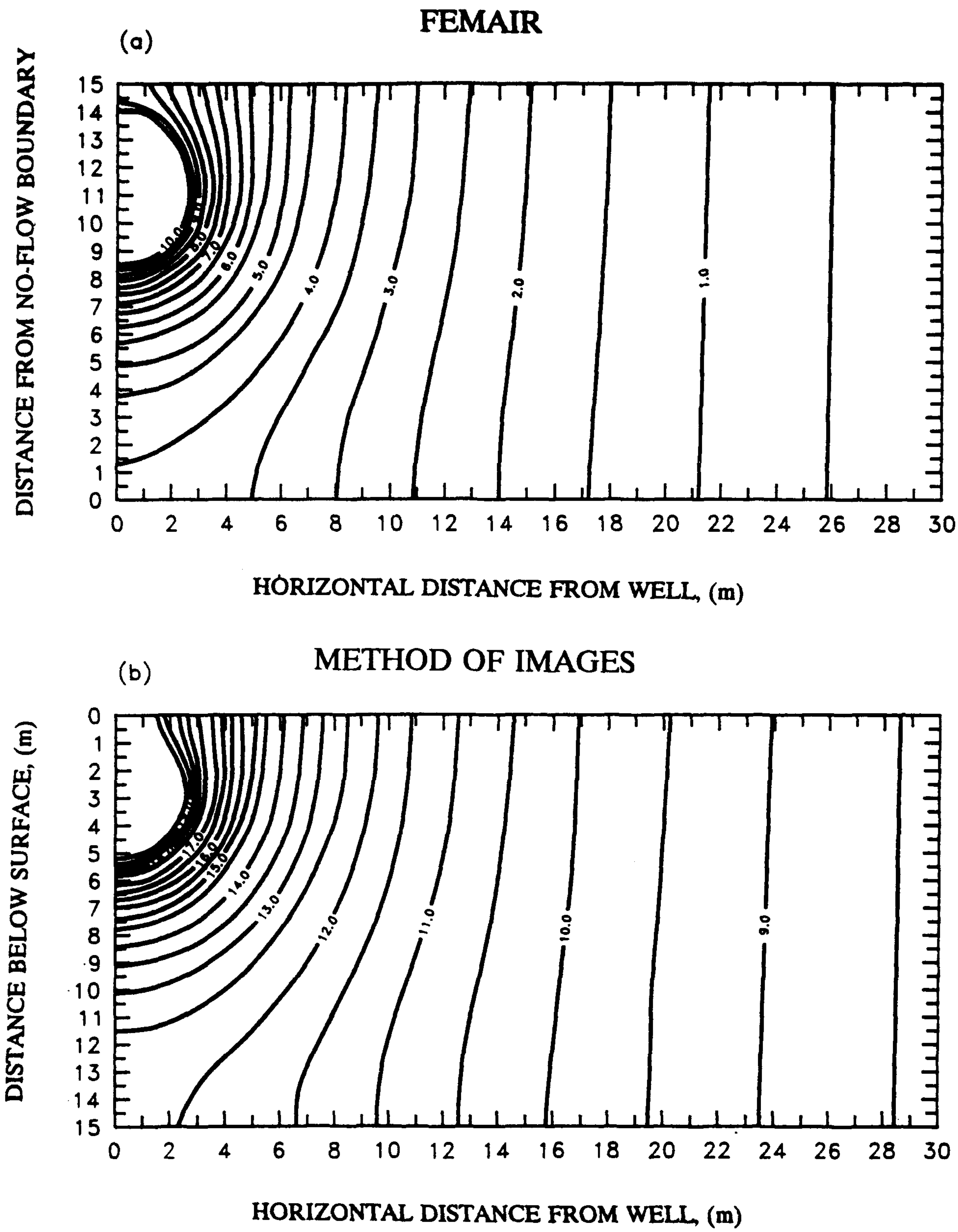


Figure 15. Comparison of FEMAIR Predictions (a) with Method of Images Analytical Model (b) for the Case of an Impermeable Surface Barrier. The Pressure Contours are Expressed in Inches of Water Below Atmospheric.

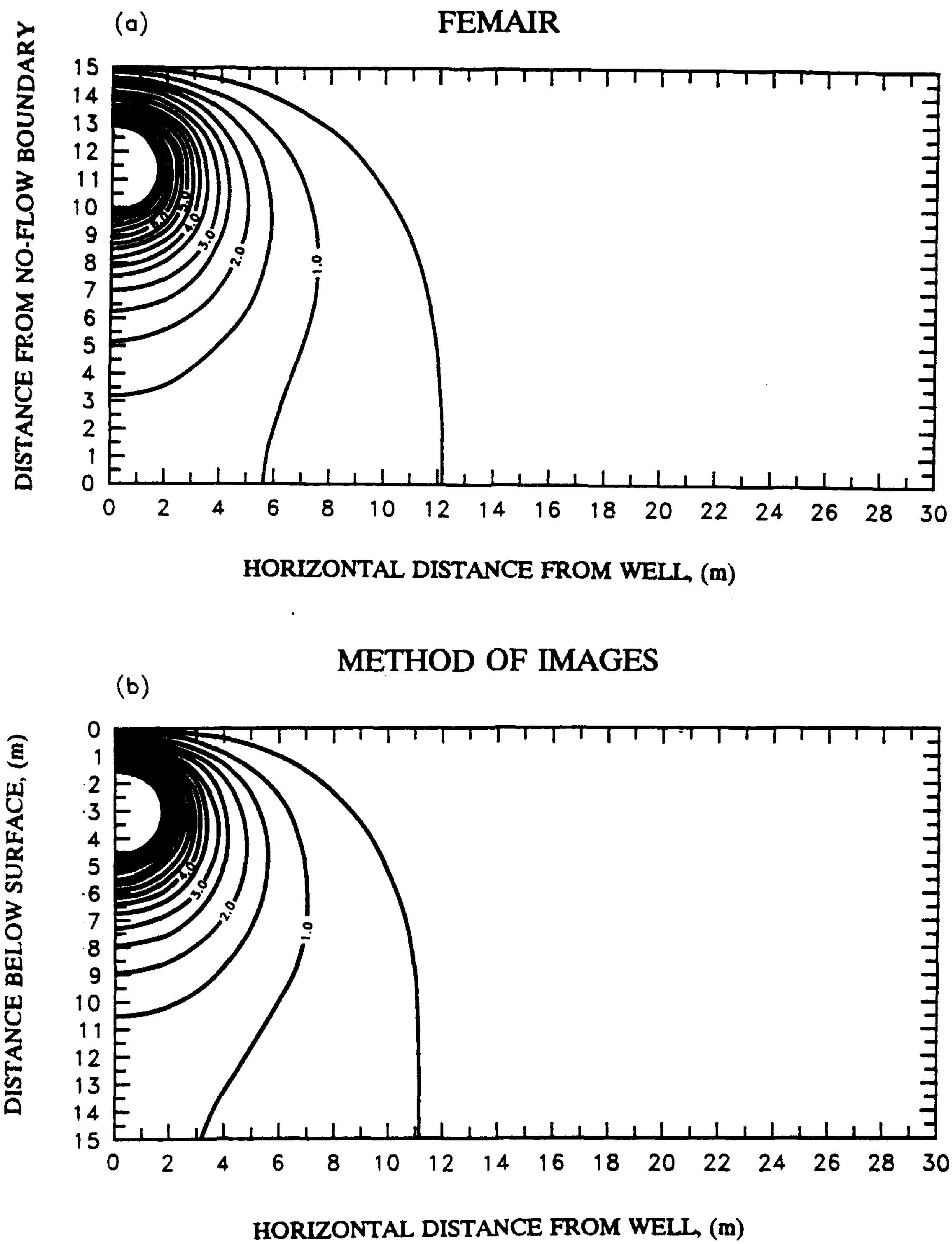


Figure 15. Comparison of FEMAIR Predictions (a) with Method of Images Analytical Model (b) for the Case of No Surface Barrier. The Pressure Contours are Expressed in Inches of Water Below Atmospheric (Concluded).

SECTION VI

IMPLEMENTATION

ISSV systems, particularly those not requiring emissions control, are relatively simple. This allows relatively quick mobilization and adaptability. These facts make an emergency response without detailed design possible, with subsequent adaptations made based on the results of operation. Therefore, a successful implementation of the technology may take one of many different forms.

The elements of implementation of ISSV are as follows:

- Full-scale Design
- System Operation
- Shut Down
- Post-operation

For larger spill sites where any remediation course will involve high cost and long operating times, all of the steps outlined may be taken before the full-scale system is constructed and operated, whereas smaller and/or emergency situations may necessitate fewer steps in the interests of cost and expediency. In the latter cases, a conceptual design such as that described in the previous section may be used as a starting point for equipment specification.

A. FULL-SCALE SYSTEM DESIGN

1. Vent Design

The conceptual design of Section IV presents a means by which the minimum number of vents necessary for cleanup of a given spill can be deduced. This treatment is based on a one-dimensional radial flow assumption. Using this flow geometry, the vent placement follows naturally by dividing the contaminated area into circles of radius r_i in the case of vertical vents and into rectangles of length L and width W for lateral vents.

Actual flow distributions in field situations will differ greatly from the one-dimensional radial flow case. Flow fields will not be simple and soil conditions will change from site to site and within a site. Therefore, some study of each case must be undertaken for optimum vent placement.

Listed below are some strategies for placement of vents, first from a general standpoint and then from a more detailed modelling approach. Flow model output is discussed here and is illustrated in Appendix E for several common cases. It is recommended that persons experienced in operation of these systems advise operators in vent placement.

a. General Vent Placement Guidelines

Vent placement must be based on the fact that contaminant removal is caused by the flow of gas through contaminated soil zones; that is, the vents must be placed to maximize intersection of the gas flow with the contaminated soil. Design schemes based solely on pressure distribution may provide inadequate treatment since air permeability may vary throughout the site and because stagnation points in multiple vent operation can have elevated vacuum levels.

A general approach to vent placement would be to position the screened portion of vents in the center of contaminated soil zones in order to have the largest amount of gas flow in these zones. The number of vents should be at least as many as predicted in the conceptual design of Section IV. The vents should be placed such that circles of radius r_i completely cover the contaminated area; however, it is recommended that more wells be placed in highly contaminated zones. These extra vents would be added to account for the interaction of multiple extraction vents and to allow flexibility for optimization of removal rate during operation.

Additional vents could be added to enhance gas flow in low-flow zones, such as stagnation points in multiple vent configurations and zones of lower permeability. The stagnation points would occur at points of symmetry in multiple vent operations. The effects of low air flow in these areas could be partially remedied by addition of passive or forced inlet vents in these positions. Further elimination of stagnation effects is accomplished by alternating the configuration of operating extraction vents. Extra vents in the less permeable zones would be necessary to increase flow if vacuum of the same order of magnitude is to be applied to these vents as the vents in zones of higher permeability.

b. Modelling as Basis of Vent Placement

As mentioned above, vent placement based on pressure distribution may not be successful since the vacuum at a point in the soil does not indicate the magnitude of gas flow through that point. Vent placement based on gas flow modelling is likely to be more successful, and a coupled flow/contaminant transport model would provide the best guidance.

Flow model output may be displayed as pressure distribution or by the distribution of the magnitude of flow. The flow contour drawings are more valuable in guiding vent placement. Points along a flow contour line receive the same magnitude of flow so they have the same potential for cleanup. By running a flow model several times with various vent placement and screening

geometries, one can tailor the vent placement to maximize the magnitude of flow within the soil zones considered to contain the bulk of the contaminants. This approach is likely to be particularly valuable in dealing with soil discontinuities and large sites in which multiple vents are necessary.

One drawback to a flow modelling approach is that it does not consider the direction of flow relative to the soil contamination. Although a soil zone may be receiving a large gas flux, the zone may be experiencing a relatively low removal rate since the gas entering the zone may have already been loaded in contaminants from surrounding zones. A more powerful approach to modelling for vent placement would be to couple the flow modelling with a contaminant transport model. With this approach, the soil contamination throughout the soil could be projected with time with each vent placement considered. A vent placement based on the desired goal, soil cleanup, would then be obtained.

Coupled flow/contaminant transport models are not reported to be in widespread use, likely due to several reasons. The first of these is the present development level of the models. Wilson et al. (Reference 37) presented a two-dimensional model based on Henry's Law of equilibrium, and Sleep and Sykes (Reference 40) described a model with multiple mechanisms. A stumbling block in the development of these models is determining the proper transport mechanism to be used. The application of even the most sophisticated models will always be uncertain due to the lack of knowledge of contaminant distribution and soil properties. Also, increasingly complex models will require increased computing power and time which may not be available in many cases.

Certainly, a flow model or a simple flow/contaminant transport model with only crude estimates of soil properties and contaminant distribution will provide better guidance toward vent placement than a rule-of-thumb approach.

Since each application will provide several varied site-specific air flow and vent placement problems, it is not possible to present a general vent placement optimization model. Rather, model simulations have been run for several characteristic flow situations. These are discussed in the following section.

c. Vent Placement Examples

The FEMAIR numerical model for air flow through porous media (Reference 36) was used to show how vent placement affects flow behavior under various ground conditions. The results of the calculations are presented in Appendix E. By identifying the flow geometries which most closely match those of the site of interest, the pressure and flow distribution diagrams presented in

Appendix E may be used to visualize the flow field induced and the zones of high and low contaminant removal. This provides a basis for adjustment of vent placement to correspond with known information on site features and contaminant distribution.

2. Vent Construction

a. Vertical Vents

Vertical vents are constructed in a manner similar to water supply or monitoring wells. The basic components are: (1) the well screen, (2) riser pipe, (3) screen packing, (4) seal, (5) surface runoff shield, and (6) protective casing. A typical vent design is shown in Figure 16. Several factors must be considered in design of vertical vents:

- The length of the screened interval must be sufficient to ensure that air flows throughout the contaminated soil zone. However, the screen should not approach the surface so closely that air flow "short-circuits" from the surface and enters the screen without having passed through the contamination zone. In the absence of an impermeable surface barrier, a reasonable minimum distance to the surface is 10 feet. Because a surface barrier reduces the potential for short-circuiting of air, a well can be screened more closely to the surface when one is used.
- The diameter of the riser pipe must be sufficient to minimize the pressure drop between the screen and the above-ground piping manifold. The resistance to air flow is greater for a screen than pipe, due to the roughness of the surface; this must be considered when determining the appropriate pipe diameter. Suggested diameters are listed in Section V.
- The pipe and screen material must be compatible with expected subsurface contaminants (see Section VI.A.4.a.). While PVC possesses many advantages (lightness, low cost, ease of assembly), it may soften in the presence of some solvents. In some cases, steel or aluminum may be preferable. Despite its relatively high cost, stainless steel may be used in some situations where solvent mixtures preclude use of plastics.
- The slot width of the screen should be sufficiently large to ensure free air movement, while small enough to prevent soil inflow into the vent well. Well materials supply companies can provide information on the appropriate screen slot size, on the basis of the particle size analysis of soil samples collected during initial exploratory boring (Section III.B.2). For sandy soil, a slot width of 0.02 inch is generally adequate.

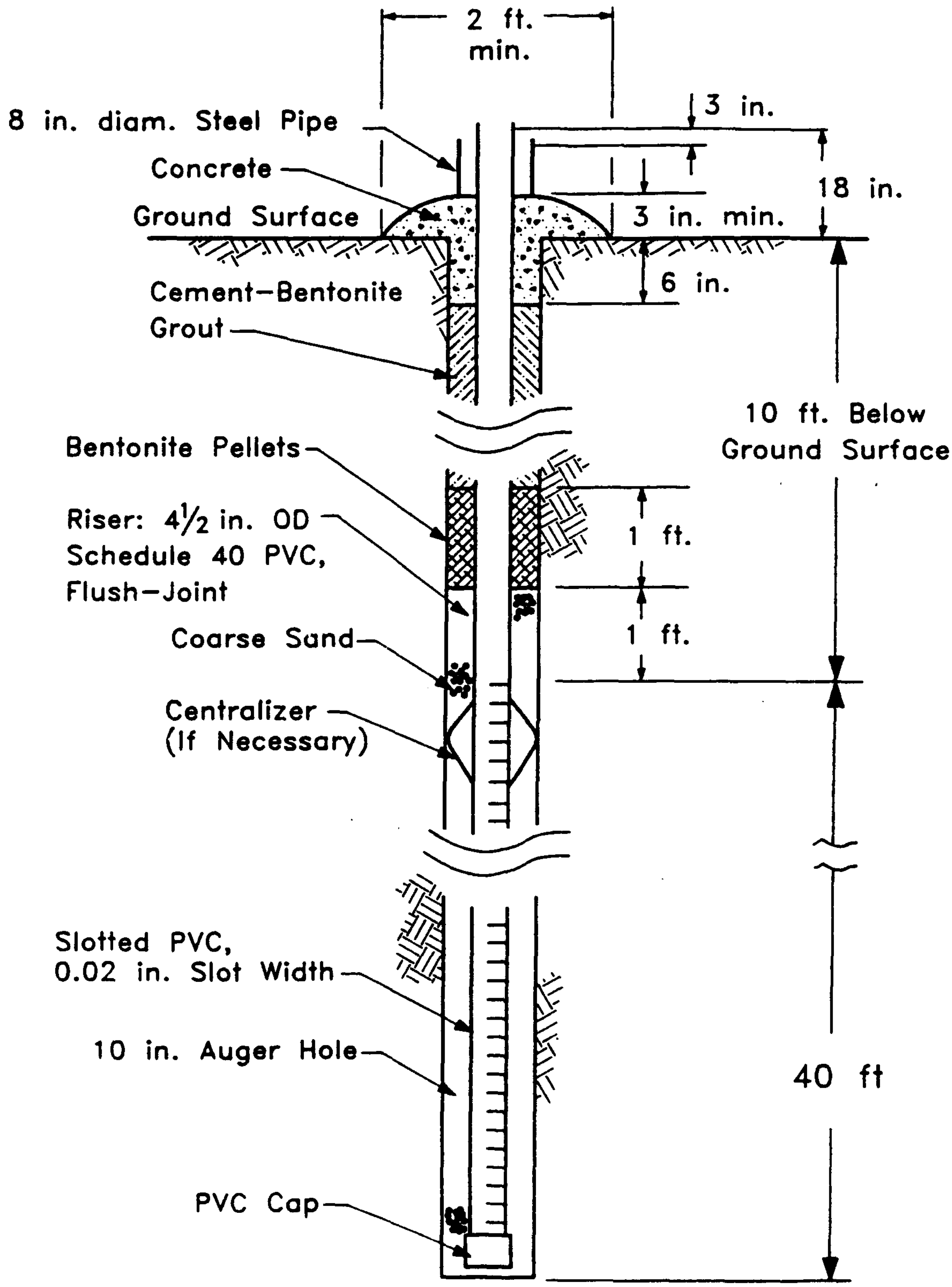


Figure 16. Schematic of a Typical Vent Well Design and Installation.

- The permeability of the screen packing material must be high enough to ensure that a pressure drop does not occur between the screen and the wall of the borehole, thereby reducing the venting effectiveness. The screen packing should generally be well-dried gravel or coarse sand (0.04-inch diameter). The screen pack should be installed through a tremie tube to ensure that it packs completely around the screen without leaving voids, which could later collapse and cause settling of the backfill and compromise the integrity of the seal.
- The seal and backfill must effectively prevent airflow from the surface along the pipe which causes short-circuiting of the contaminated zone. The seal may be bentonite pellets (especially in the presence of wet soils), a bentonite-cement grout mixture, or cement. Clean soil may be used to backfill above a seal to the surface. As with the screen pack, a tremie tube should be used to install the seal.
- The surface should be sealed with a concrete collar to ensure sufficient physical stability of the vent well so that it is not dislodged during assembly of the manifold, and to prevent rainwater infiltration along the vent pipe. A protective steel casing and locking cap may be installed to protect against tampering prior to installation of the manifold piping. Protective posts may be installed if the venting operation is in an area where vehicular traffic may present a risk of damaging the well.

If boreholes remain open without collapsing, vent pipes may be installed after completion of the borehole. If vents are to be installed after removal of auger flights, the diameter of the auger should be at least 4 inches greater than that of the vent screen and riser pipe to ensure adequate annular space for effective installation of the screen pack, seal, and backfill.

If exploratory boring has shown that boreholes do not remain open, the vent screen and riser pipe may be installed through the hollow stem of a continuous-flight auger. A 10-inch diameter auger is required to install a 4-inch outside diameter vent pipe. Alternatively, a temporary casing, through which the vent well may be installed, may be installed during either augering or drilling with a cable tool.

b. Lateral Vent Construction

If contamination may be confined to the upper soil zone [e.g., 10 feet below land surface (BLS) or less], either because of the presence of a shallow water table or because the spill is sufficiently recent that further downward penetration has not occurred, use of lateral vent pipes may be preferable to vertical vent wells. Lateral vents must be designed to permit maximum air movement

through the full depth of the contamination zone, with minimal pressure drop within the pipe or the material immediately surrounding the pipe. The pipes must also be sufficiently strong to avoid collapse, and preferably low in cost.

An effective design in the Hill Air Force Base study involved use of 4-inch diameter perforated polyethylene drain pipe (highway-grade; AASHTO-M252 specification) for the horizontal vent pipes, with nonperforated pipe of the same thickness attached to the ends with duct tape to serve as risers to the surface. The horizontal pipes were installed in trenches approximately 5 feet to 6 feet deep and 18 inches wide, backfilled with gravel to within 1 foot of the surface. The surface of each trench was then sealed with concrete. Due to the reuse of the site at Hill AFB, the vented zone was sealed with a layer of concrete, which prevented air movement downward to the lateral pipes from the surface. Polyethylene sheeting would have accomplished the same purpose had the cement foundation not been necessary.

3. **Equipment Needed**

The following above-ground equipment is in common use in ISSV application.

a. **Mandatory Equipment:**

- Piping of sufficient size and quantity.
- Valves of sufficient size and quantity.
- Vacuum blowers of sufficient vacuum and flow capabilities.
- Vapor/water separator (knockout drum).
- Instrumentation for the measurement of vapor flow rates.
- Instrumentation for use in on-site monitoring the hydrocarbon content of the vapor stream.
- Electrical power hookup and controls.
- Safety-related equipment.
- Emissions control equipment may or may not be mandatory depending on regulations at site

b. **Optional Equipment:**

- Instrumentation for measurement of various gas properties such as temperature, humidity, and CO_2 and O_2 content.
- Instrumentation for measurement of various ambient conditions such as barometric pressure and temperature (this would be more applicable to research projects).
- Piping insulation for exposed pipes if the application is susceptible to the formation of condensate in pipes due to temperature differences.
- Surface barrier of impermeable media.

4. Equipment Selection

a. Piping.

All piping and related equipment should be sized according to common engineering methods such as outlined in the Chemical Engineers' Handbook (Reference 41) or other comparable engineering design textbook. Piping and related equipment are available in a wide variety of materials. Piping materials must be compatible with the process fluid, and it is crucial that the pipe wall thickness must be sufficient to withstand pressures or vacuums that may be applied. Vendors can supply information regarding common piping materials and their compatibility with some common fluids. PVC is one material that is commonly used, easy to work with, and allows for easy field modification and repair. PVC reportedly has been used successfully in gasoline and JP-4 fuel spill remediation by venting. Valves and other fittings of PVC are available in a large size range almost anywhere in the country. One drawback of PVC is deterioration due to sunlight. Paint or insulation is suggested for long-term exposure.

For some soil-venting applications it will be advisable to insulate and/or heat-trace the process piping. This is especially true where pipe systems will be exposed to low wintertime temperatures. Self-regulating heat-trace tape, rated at various maximum temperatures, is probably the best choice due to the fact that it does not demand a separate temperature controller. This helps prevent overheating of process piping, which is very important when dealing with plastic pipes or volatile organics. Be aware of the maximum temperature rating of the piping material at a given pressure or vacuum in contact with the contaminants. When heat tracing soil-venting pipe, be sure that all electrical sources are kept from any possible contact with the process vapors through the use of connectors and/or temperature control switches of the proper classification. Drain taps are also suggested at low points in the piping system to allow for drainage of condensate when necessary. Draining of the system will have to take place with the system shut down or that section of pipe disconnected from the vacuum source.

b. Valving.

When selecting valves for soil venting applications, attention must be paid to material of construction of both the valve body and internal components for compatibility with contaminants. The type of valve used for a given application will be determined by its function. Control valves should be used for dilution inlet air, if needed. Wafer type butterfly valves are a good choice where precise control is not necessary. These valves are available in PVC with Viton internals, which are

suitable for fuel hydrocarbons. They are easily installed between pipe flanges and provide visual indication of valve position by observing the valve handle position. Valve cost depends on the size and material selected.

c. **Blower.**

A wide variety of blower types and sizes has been used successfully for ISSV demonstration systems. Conventional fan-type blowers, positive displacement blowers, centrifugal blowers, liquid ring pumps, and rotary-vane vacuum pumps were reported for the demonstration systems reviewed. Blowers ranging from 10 to 9500 ft^3/minute capacity and 0.5 inch of water to 29 inches of mercury vacuum have been used.

The selection of a blower for a system depends on site-specific conditions, such as soil permeability and size of the spill site. If possible, selection of a full-scale blower should be made after a pilot-scale test at the site. General suggested guidelines are for 25 inches of water column (6220 Pascals) vacuum or greater for sandy soils, and greater than 8 inches of mercury column (27000 Pascals) vacuum for less permeable soils. Use of an air flow model, normalized plots of vacuum requirements, or analytic equations for radial flow, as described in the conceptual design of Section IV, are helpful for determining blower requirements. The pressure drop that will occur in the piping system itself should also be included. It is recommended that blower capacity and vacuum be oversized somewhat to allow for uncertainty in requirements and flexibility in operation. Either the blowers should be spark-resistant with explosion proof motors, or the installation should include flame arrestors and explosive atmosphere detectors.

Another consideration when designing blower systems is that several options exist for providing for a range of vapor flows rates for a given application. A single blower controlled by some type of motor-speed (frequency) controller may provide flow rates for any given situation. A consideration when choosing the option best suited for a given application is that frequency controllers tend to be somewhat expensive. Remember, however, that reducing motor speed may make the process more efficient than flow control using valves and can offset some of the initial cost of the frequency controller. Multiple blowers can also be installed to pump in parallel rather than having a single large blower.

Blowers can be specified in terms of the maximum vacuum and flow rate desired. With this information, vendors of blower packages will be able to select the appropriate size and type of blower. Generally, as long as the blower can provide adequate flow and vacuum, it will be suitable; the type is not critical. However, several factors should be considered before making a selection, such

as: (1) If the blower may be used for several applications, make sure that the blower capabilities are greater than the minimum which will meet the immediate needs. A larger blower with a larger motor than needed using a pulley ratio to bring it to the appropriate speed may be used at more sites than a blower designed for the single site specifications; (2) Some blower designs may make them more susceptible to disruption by changes in temperature or by particulates, making design adaptations necessary. Read the vendor literature to check for any suggested limitations in operating conditions; and (3) Some blowers are normally manufactured out of spark-resistant materials such as aluminum, whereas others must be specially constructed to make them spark-resistant leading to higher cost and longer delivery times.

d. Vapor/Water Separator (Demister)

Most venting applications include a vapor/water separator or demister in the piping to protect the blowers from particulates or water droplets. Considerable water uptake by the venting air may occur and could cause operational difficulties if allowed to enter the blower. A wire mesh is a common type of vapor/water separator that has been used successfully in soil venting applications. This type of separator usually consists of a bed of interlocking fine wire woven together and supported horizontally in a separator vessel by support rings at the wall of the vessel. The mesh pad normally has between 97 and 99 percent free volume. Gas flows upward through the mesh and the liquid particles impinged on the wire by their forward velocity are collected at the bottom of the separator vessel. Free liquid can then be removed from the separator vessel by a pumping system or drained during shutdown operations.

Design criteria can be found in the Chemical Engineers' Handbook (Reference 41) or other chemical engineering equipment design textbooks. Demister pads and other type of impingement separators are available commercially. Manufacturers are very helpful in assisting potential customers with a design for their particular application. It is suggested that the manufacturer be consulted for design or design verification before ordering or fabricating a demister system.

e. Surface Barrier

A design consideration for improving performance of an ISSV system is the addition of an impermeable surface barrier over a'l or part of the contaminated soil area.

A surface barrier may be used to prevent percolation of rainwater into the soil, thereby retarding transport of the contaminants and also improving air permeability of the soil. For this purpose, it is recommended that a surface barrier be installed immediately at fresh spill sites, particularly those in areas of high rainfall.

Surface barriers are also useful for preventing vertical air flow at the soil surface, thereby shifting the air source from the surface near the extraction vents to soil areas outside the covered zone. This causes a more horizontal flow pattern for better vertical distribution of flow and a larger radius of influence. Surface barriers may be particularly effective at sites with shallow contamination. Sites with stratified soils may already have an effective surface barrier.

Several materials have been reported to be used for surface barriers, including concrete, clay, and polyethylene sheets covered with soil. Concrete may be less attractive if the site is to be used for some other purpose after venting is complete, and clay may not be applicable for arid climates since it may dry and crack (allowing flow-through) or blow away.

f. Emissions Control

A necessary part of an ISSV system is often a process to control final emissions of hydrocarbons to meet regulatory discharge limits. Emissions control is a major cost factor for ISSV systems, amounting to 20 to 50 percent of total installation and operating costs (Volume I).

Because of the nature of extracted gas from these systems, usually of high humidity and varying over several orders of magnitude in contaminant concentration, selection of optimal emissions control processes may be difficult. The choice of a particular option will be driven mainly by economics and by regulatory approval. Section VII presents an economic model of soil venting which may be used for guidance in selection of an emissions control device. This section provides a short description of common processes that are feasible for use on a soil venting system, including carbon adsorption, condensation, thermal or catalytic oxidation, direct discharge to the atmosphere, and other site-specific solutions.

Carbon adsorption is likely the most widely used emission control technology for soil venting systems. In this process, vapor-laden air is passed through beds of activated carbon. Adsorption of volatile organic compounds is dependent on relative humidity, temperature, concentration and type of organic compound, and regeneration steps used (Reference 11). Carbon beds are used until breakthrough of organic constituents occurs. The carbon is then either discarded, if used in small quantities, or regenerated. Regeneration can be performed onsite with the proper equipment, such as a steam system and condenser, or the carbon may be transported to the vendor.

Because of uncertainties and wide ranges of contaminant concentration and composition in soil venting off-gas, it is difficult to estimate carbon consumption before operation. Recommended additions to a carbon adsorption system to reduce carbon consumption include a demister or a condenser upstream to reduce water content and (possibly) contaminant concentration and temperature control (usually preheating) to reduce the relative humidity in the stream feeding the carbon bed.

Carbon adsorption is an attractive choice for emission control since it is a widespread and proven technology; however, the cost of carbon and regeneration may be quite high. Also, carbon adsorption does not solve final destruction problems, since the hydrocarbons retain their composition even after regeneration.

Condensation is a hydrocarbon vapor reduction step that employs chilled surfaces to liquefy water vapor and organics in an air stream. It is limited by the vapor pressure of each constituent, being most effective with the least volatile compounds. Because of this fact, it is not likely to be successful as the primary emission control step for an ISSV system. To reach temperatures where emission of hydrocarbons would be greatly reduced, the condenser may encounter operating problems due to freezing of water vapor from the nearly-saturated extraction air. Condensation may prove to be economical in high concentration, high humidity air streams to reduce the load on other emissions control processes, such as carbon adsorption. Another consideration is the production of water with possible hydrocarbon contamination.

Thermal and catalytic oxidation are attractive emission control steps both in terms of economics and final destruction capability. In these processes, the vapor-laden air is heated to a temperature high enough to oxidize the hydrocarbons, as in the case of thermal oxidation, or to a relatively lower temperature followed by contact with specific catalysts as in the case of catalytic oxidation. Thermal oxidation consists of a burner in which the vapor-laden air stream is used as combustion air. The simplicity and high final destruction of volatile organics may be offset by the high energy requirements for this process. Johnson et al. 1989 (Reference 1) suggest a lower concentration limit of 10,000 ppmv for economic usage of thermal oxidation.

Catalytic oxidation is a promising process in which a catalyst is used to promote the oxidation of organic compounds. A typical system is usually composed of four basic parts. A preheater is used to bring the temperature of the incoming gas stream to a suitable temperature, typically 600°F or above. A mixing chamber after the preheater promotes uniform temperature in

the gas. The catalyst bed may be either fixed or fluidized, and is composed of finely divided precious metal or a metal oxide on metal or ceramic supports. A final heat recovery stage is optional.

Because of their simplicity, fixed-bed systems are the more widely used catalytic oxidation devices in industry. Problems that can occur, however, are deactivation of the catalyst due to poisons such as halogens and sulfur compounds, and fouling by dust. Fluidized bed systems solve some of the fouling and deactivation problems of the fixed bed systems by replenishment of catalyst and abrasion of the surface of the catalyst pellets. However, fluidized bed catalysts do not use precious metals. Also, backmixing of the gas occurs in fluidized beds, whereas the fixed bed essentially operates at plug flow conditions. Thus, fluidized bed systems may need to be operated at higher temperatures than fixed bed units to achieve the same destruction efficiency.

A Weston study (Reference 42) found catalytic oxidation in use with ISSV systems to be economically attractive. The Hill Air Force Base demonstration provided one of the first documented cases of catalytic oxidation in combination with soil venting. This demonstration found both the fluidized- and fixed-bed systems to perform successfully with few operational problems and low maintenance. Johnson et al. (Reference 1) suggest an upper limit of ~8000 ppmv for these units because of overheating. The extracted gas from the Hill Air Force Base system was diluted during the early phases of operation to account for this problem.

In certain cases, extraction air may be directly discharged to the atmosphere, with regulatory agency approval. Since the only system requirements are air dispersion stacks, this technique is by far the most cost effective. In fact, some systems have been operated below design venting rates in order to stay within discharge limits (References 18 and 43).

Other innovative and often site-specific solutions to ISSV emission control problems have been implemented to reduce costs. Extraction air has been piped to on-site boilers to be used as combustion air (References 8 and 44), as in a thermal oxidizer. Another system was connected to the existing air scrubber of a building (Reference 23). The self-contained unit reported by Rippberger (Reference 45) not only destroyed the contaminants, but powered the venting process. A process common in Europe and Japan, but only slowly gaining popularity in industrial applications, is the use of biological beds for off-gas (Reference 46). This process could provide cost-effective emission control for soil venting applications.

g. Flow Monitoring Instrumentation.

Measurement of flow rates at various points in the soil-venting system is necessary for reliable operation and for determining emissions for material balances and compliance for local and

state regulators. There are several types of devices on the market for flow rate measurement. Some of the more common devices are orifice meters, venturi meters, rotameters, pitot tubes, hot-wire anemometers, and mass flow meters. A short discussion of each follows:

- Orifice Meter - This is one of the simplest, more robust, and most accurate flow measurement devices available. A disk with a round orifice in its center is inserted into a pipe (usually between pipe flanges) perpendicular to its flow. The pressure drop of the fluid across this constriction is measured and correlated to the flow rate. The size of the orifice is determined by the flow range to be measured. In addition to pressure drop, one must also measure the density, temperature, and viscosity of the fluid in question. Notes on how to size and construct orifice meters can be found in Reference 41.
- Venturi Meter - A venturi meter works basically on the same principle as the orifice meter. It involves measuring the pressure drop across a well-defined constriction in the pipe's cross-sectional area. This is a very reliable, relatively maintenance free device. It is usually somewhat more expensive than an orifice meter to fabricate or install, but it is equally well-suited to soil-venting applications.
- Rotameter - A rotameter, generally restricted to low flow rate measurements, is essentially an orifice meter of variable area and constant pressure drop. A rotameter consists of a plummet which is free to rise and fall in a tapered calibrated tube. Fluid enters the lower end of the tube and causes the plummet to rise until the pressure drop across the space between the tube wall and the plummet is just sufficient to support the effective weight of the plummet. The tube and plummet must be calibrated to the particular fluid being pumped. Correction factors, for temperatures and gas density, may need to be applied.
- Pitot Tube - This device measures flow rate by measuring the difference between the impact pressure and the static pressure of the fluid. It consists of a small tube which is either inserted or installed through the wall of a pipe and some type of external gauge for measuring pressure differential. The advantage of this device is that there is very little loss in fluid pressure. A disadvantage is that, while the orifice meter and the rotameter may be used to determine the total rate of flow of a fluid through a pipe, the pitot tube is used to find the rate of flow at just one point in the cross-sectional area of the flowing stream. This requires traversing the cross-section of the pipe to get an average value. It is, therefore, subject to errors based on placement

of the measuring device inside a pipe. An insertion-type pitot tube instrument also makes a handy tool for spot-checking fluid flow.

- Hot-wire Anemometer - This instrument's principle of operation is based on the temperature differential measured between a heated and non-heated portion of a probe that is inserted through the wall of a pipe perpendicular to fluid flow. It can be used only with non-explosive fluids in non-explosive atmospheres. It is subject, however, to the same errors as pitot tubes in that its accuracy depends upon careful placement of the probe inside the pipe.
- Mass Flow Meter - Electronic mass flowmeters utilize thermodynamic principles to measure the true mass flow rate, without temperature or pressure compensation. There are basically two types of electronic mass flow meters available today; the heated tube and the immersion probe. The heated tube type is only applicable to processes that contain clean gases. For soil-venting purposes, a discussion of this type will not be included. The immersion probe type, on the other hand, is more rugged and may have suitable application to soil-venting projects. The operational principle of this instrument is based on heat lost to a fluid flowing past a heated probe. The heat transfer rate can be connected to the mass velocity of the gas by electronics designed for this purpose. Mass flowmeters, in general, are expensive, but are precise flow measurement devices. Remember, however, that a potential safety hazard is introduced when any electrical device contacts an explosive atmosphere. Therefore, suitable safety precautions should be taken.

The above devices are some of the most commonly used to detect and measure flow rate. They are by no means the only ones suitable for the job. The choice of flow rate monitoring instrumentation should be based on the best apparatus for the overall system design. From experience, we would tend to recommend the orifice meter due to its simplicity, cost, ease-of-use, and reliability. Other devices may be better suited to certain applications at some sites.

h. Hydrocarbon Monitor.

To monitor progress while operating a soil-venting system, the total hydrocarbon content of the extraction vapor must be known. To measure this parameter continuously, a Total Hydrocarbon Analyzer or equivalent instrumentation is recommended. This instrument contains a Flame Ionization Detector (FID) with associated valves, gauges, and electronics for detecting and quantifying the total hydrocarbon content of the sample stream. This instrument works best for fuel

hydrocarbons, whereas an instrument containing an Electron Capture Detector would be more sensitive to chlorinated hydrocarbons. None of the sample must be allowed to condense inside the sample line to the analyzer. To prevent this, sample lines should be heated to slightly above process temperature. Standard gases consisting of a pure gas or gas mixture that most closely represents the sample stream are required for calibration of this instrument. Hexane standards were used in the Hill Air Force Base demonstration for comparison with JP-4.

A gas chromatograph, either a field model or laboratory model housed in an analytical facility, may be used to provide the capability for monitoring the distribution of certain organic constituents in the extraction vapor. Hydrocarbon distribution may be used to indicate which zones of soil are better treated by determining the average hydrocarbon weight in the extraction vapor.

i. **Safety Systems.**

In Soil Venting, as in any endeavor, personnel safety and protection of equipment and facilities are of prime concern. Consulting with local fire and safety regulatory agencies is strongly recommended as a primary task when approaching any soil venting project. A comprehensive Safety Review by the appropriate authorities is required. Listed below are several design features used in the Hill Air Force Base demonstration to account for safety concerns.

- Explosion-proof liquid level switches in knock-out drum.
- Explosion-proof temperature switches on heat tracing tape near or within Class 1 areas.
- Spark-resistant (aluminum) internals of blower or flame arrestors at inlet to blowers without spark-resistant internals.
- Explosion-proof motor on blower, or combustible gas detector placed in ambient air in area of TEFC (totally enclosed, fan-cooled) motors, with output controlling electrical shutdown breaker.
- Combustible gas detector plumbed into piping, with output controlling electrical shutdown breaker.
- Two combustible gas detectors mounted in analytical trailer, one at ceiling and one near floor, with output controlling electrical shutdown breaker.
- Warning relays on incinerators (signalling flame-out or high temperature alarms) connected to electrical shutdown breaker.

- All electrical wiring and control boxes of NEMA 4X rating, outside of National Electric Code Class 1 areas, required explosion-proof within. All electrical equipment grounded and with overload protection.
- Propane tanks located in accordance with NFPA 58.
- Silencers on blower inlets and outlets.
- Flow restrictor on hydrogen fuel cylinders for analyzer.
- Eye protection required. Hearing protection and respirators available.
- Portable combustible gas indicator and photoionization detector available for ambient air monitoring.
- Fire extinguishers available.
- Site-specific safety training for all personnel.

The most important of these safety features are the automatic shutdown system and safety training for personnel. Various electrical safety shutdown methods can be applied in any given application. One must determine the most appropriate one for the situation at hand. In any event, some type of electrical safety shutdown should be employed to prevent accidental injury to personnel or equipment destruction. In most cases, this involves sensors and electronics that shut off electrical power when specified limits for organic vapors in the piping or the ambient air are approached.

Each project will be unique, but the above list can serve as a general guide to promote awareness of potential safety related issues.

j. **Electrical Power Source.**

One of the primary elements of any project, such as soil-venting, that may seem obvious is an adequate supply of electrical power. The not-so-obvious need is for this power to match the specifications of the equipment that will be installed. For instance, the amperage needed to power a 10 hp blower motor may be supplied as 110 volt, 220 volt, or 440 volt alternating current. The motor may require single-phase or three-phase hookup. Make sure the correct power source is available at the site or can be readily connected. The expense of electrical power hookup may be offset by ordering motors and electrical components that comply with the requirements of the site.

Another consideration when specifying electrical components for use at soil-venting sites is the electrical code that is enforced at the site or at different locations within the same general area. Electrical components may need different classifications depending on the zone in which they are located. This is generally determined by proximity to combustible or explosive materials. The electric code may dictate specifications for enclosures for motors, switches, heaters, and other equipment. It would be advisable to become familiar with Articles 501, 514, and 515 of the National Fire

Protection Association's code. Local Safety Offices and Fire Departments that have site jurisdiction should be consulted before specifying, ordering, or installing any electrical apparatus in an area in which combustible or explosive materials may be encountered.

k. Miscellaneous/Optional Equipment.

Various supporting equipment items are needed to operate the soil venting system. Some of these items are addressed below.

Calibration gases will need some attention on the part of the operator. These gases can be obtained in small or large cylinders and must have an adequate and appropriate storage facility. Gas cylinders must be fitted with the correct pressure regulator and an appropriate gauge for its application. Consider the ambient conditions to which gas cylinders will be exposed. Low ambient temperatures may cause condensation within the cylinder and give erroneous readings when calibrating instrumentation.

Fuel, such as liquid propane gas used to operate incinerator units, should be supplied in large tanks unless natural gas lines are available. These tanks usually can be rented from the gas supplier. Adequate space must be reserved for tanks which must be in a position that will allow for easy access by trucks to fill them periodically.

Assorted pressure gauges are handy items to have on hand for various operational and testing procedures. If the operating parameters of the soil venting system, e.g., vacuum, are adjusted for any reason, a gauge of an appropriate range will be needed. Remember that gauges must be durable if installed outside or subjected to hostile environments.

A pump may be needed to remove any condensate collected in the vapor/water separator. The required size of the pump will be determined by the amount of condensate expected. This pump can be installed with a liquid level control switch to provide automatic drainage of the separator vessel. A pump will be needed only if the vessel is drained while the process is under vacuum. The vessel can be drained by gravity when at atmospheric pressure, such as when the process is shut down or bypassed.

If the process vacuum blowers that are selected for your particular soil venting application are extremely noisy, silencers should be installed. These silencers are installed on the blower discharge and/or suction side. They can be somewhat expensive and should be ordered with the blower package to assure compatibility with the blower and associated equipment. These silencers are included as standard equipment with some blower packages. Be sure to check this with the manufacturer's representative before ordering.

Some other considerations are listed below. While some of these items are optional, others may be mandatory depending upon the application.

- Gas sampling equipment
- Fuel for flame ionization detector
- Various calibration kits for instrumentation
- Supply of heat tracing wire and controller
- Insulation for pipes, tubes, etc.
- Spare parts for crucial equipment

When selecting any equipment for a soil venting application, keep in mind that the equipment selected may add to the total manpower required to carry out the project. By spending a little more capital during the initial project phase, one can reduce maintenance and manpower-intensive tasks.

B. OPERATIONAL STRATEGIES

With vents placed in or near the contaminated soil zones, extraction of soil gas will eventually result in cleanup of the site. However, certain strategies in operation are suggested for timely and economical remediation.

1. Initial Operation/Dilution

During the initial operation of a venting system, the gas extracted will have elevated contaminant levels, often well above the lower explosive limit. Therefore, precautions must be taken to avoid hazardous conditions. In addition to the safety systems described in Section VI.A.4.i. (such as flame arrestors, spark-resistant blower internals, and automatic shutdown systems), the system should be operated with dilution of the extracted gas to maintain gas contaminant levels below that which is considered safe for operations by local safety regulations.

Dilution of the extracted gas may be performed either by introducing atmospheric air into a dilution tee in the piping system, or by extracting gas from a perimeter well. In the latter case, the dilution of the gas essentially takes place in the soil. This technique has two advantages: (1) more oxygen may be supplied to the soil with the greater air flow, possibly enhancing biodegradation and (2) the warm dilution soil gas may prevent condensation and freezing in the piping which may occur under certain ambient temperature and humidity conditions during atmospheric dilution. Dilution using a perimeter vent has disadvantages, however, such as (1) the contaminants may be transported from contaminated soils and deposited on cleaner soils in the area of the perimeter vent, and (2) problems from an operational standpoint may occur since the extracted gas contaminant concentration in the perimeter vent is likely to increase with time, making control difficult.

Dilution is particularly important when the system includes emissions control devices. Concentration levels or flow rates may need to be limited in order to allow reasonable cycle times for carbon adsorption beds. In cases where the carbon is to be transported off-site for regeneration, the concentration may have to be limited. Catalytic oxidation units are limited in the allowable temperature rise across the reactor beds due to contaminant oxidation. Fluidized bed units generally allow a greater temperature rise than that of fixed bed units. Vendors of these units will state the maximum temperature and temperature rise for which their units are designed. The potential temperature rise may be calculated using the heat of combustion and concentration of the contaminants. A rule of thumb for estimation is that 20-25°F temperature rise will be generated for every 100 ppmv of fuel hydrocarbons (depending upon the average molecular weight of the contaminants); however, this value may vary, depending on the amount of contaminants oxidized in the preheater.

Since contaminant concentrations are likely to decrease rapidly in the initial stages of venting, the dilution ratio will need to be changed frequently for optimum operation. For larger systems, it may be economical to control dilution using an on-line analyzer or a temperature signal from an incinerator as the input signal to a controller operating a control valve on the dilution line. This controller could be set to keep the concentration at a level which would give a certain bed breakthrough time in the case of carbon adsorption, or maximize the catalyst temperature rise for an optimal removal rate.

2. Pulsed Operation

Several investigators have suggested that pulsed operations (that is, intermittent operational periods with shutdown periods) will lead to a more economical remediation. This is due to possible diffusional effects upon the removal rate, which will most likely be encountered when free product is present on the water table or in confining layers where contaminants are held in less permeable soil zones surrounded by fractures or by more permeable soil.

A method of determining if contaminant removal is controlled by diffusion is a shutdown test, as described in Section V.B.3. If there is little diffusional resistance, pulsed venting will yield no advantage. Whether the shutdown period was sufficient for re-equilibration should be checked, possibly by running several tests of various shutdown period lengths. The presence of diffusional effects may also be checked by running tests at different flow rates; at lower flow rates the diffusional effect should be less.

Pulsed operation will result in a longer total time for cleanup than continuous operation. However, pulsed operation causes higher extracted gas contaminant concentrations, resulting in lower blower and emissions control costs per mass of contaminant removed. In general, if emissions control is not required and blower operation is not overly costly, pulsed operation may not be advantageous. For cases involving an emissions control device (whose operating cost depends upon contaminant concentration) or high vacuum requirements, calculations to determine if pulsed operation is economical are recommended.

For larger sites, a better operating strategy is to vary vent configurations, as described below.

3. Operation of Vents

The determination of which vent wells to operate to achieve optimum extraction would be complicated from a modelling standpoint. For reliable results, one would need a very detailed site characterization and complex models which have not yet been demonstrated. A modelling approach is, therefore, well beyond the scope of this document and most applications. The approach taken here assumes a reasonable distribution of vent wells and outlines a strategy based on field observations for vent operation.

For good performance of a soil venting system, the vent wells must be placed throughout the contaminated soil area. Areas of high contamination and zones of low permeability (or high bulk density) will be benefitted by a higher concentration of vents (smaller vent spacing) (Reference 47).

During the initial portion of operation (see Section VI.B.1), as long as dilution is necessary it does not matter which vent is operated. During this period, the emissions control system dictates the contaminant removal rate. The vents should be operated to stay within this regime as long as possible.

Once the off-gas concentration in all vents has fallen below the emissions control system limit, those vents which maximize removal rate by maximizing concentration should be operated. A strategy of extraction which involves the vent combinations yielding the most concentrated soil gas should provide the best means of decontamination by volatilization, since the maximum gas concentration should correspond to the highest soil concentration. It should be noted, however, that such a strategy also involves increased supervision. Maximizing off-gas concentration will most likely be done by extracting gas from vents centered in the contaminated zones. It should be noted that multiple operating vents will set up more complicated flow patterns, which may exclude highly contaminated zones. Therefore, several venting configurations should be operated to determine the highest concentration achievable. It may be useful to operate some of the vents in the center of multiple

extraction vent arrays as passive or active air inlet sources. It is unlikely that simultaneous extraction from all vents will give the best removal rate, particularly for a grid arrangement since zones of lower air flow may occur within the overlapping zones of influence of each vent.

As soil zones are decontaminated, the relative contamination of different zones changes. The off-gas contaminant concentration from each vent should be checked periodically to direct changes in operation. Each change in operation should be adequately documented in order to prove, during regulatory review for site closure, that all contaminated soil zones have been treated.

A mode of operation, similar to the pulsed operation described in the previous section, may be successful at larger sites for maximizing removal rates. In this mode, one would periodically switch the operating area of vents from one side of a site to the other. While one side was operating, the other would be re-equilibrating if diffusion was important in removal.

4. Heat-Enhanced Soil Venting

Soil temperature has a profound effect on the contaminant removal rate, mainly due to the increase of contaminant vapor pressures with increased temperature. An illustration of this may be seen in Figure 17, which shows removal curves generated by an equilibrium model for JP-4 spills in soils of 50°, 75° and 100°F. The volume of extracted gas necessary for cleanup decreases dramatically with increased soil temperature. This accelerated removal would prove valuable in cases where a short cleanup time is necessary, low air permeability of the soil leads to high blower operating costs, or emissions control operating costs are high. Heating the soil would lessen emissions control costs both by reducing the time of operation and by raising the concentration of the gas fed to the emission control device.

Major drawbacks to heat-enhanced removal are the large quantity of energy necessary to heat the soil and maintain the temperature, and finding a method of delivering the heat evenly and cheaply. Some of the methods currently considered are heated air injection, steam injection, and radio-frequency heating. Hot air injection suffers both from high energy cost and uneven heat distribution due to radial flow outward from an injection point. The cost may be significantly reduced if the energy is derived from a waste heat source, such as incinerator stack gas. Steam injection may provide some cost savings, but distribution remains a problem. Also, steam condensation introduces the problems of higher soil moisture, such as reduced air permeability, higher water uptake by the venting system, and solubility and possible contaminant transport. Radio-frequency heating may solve distribution problems, but cost remains a factor.

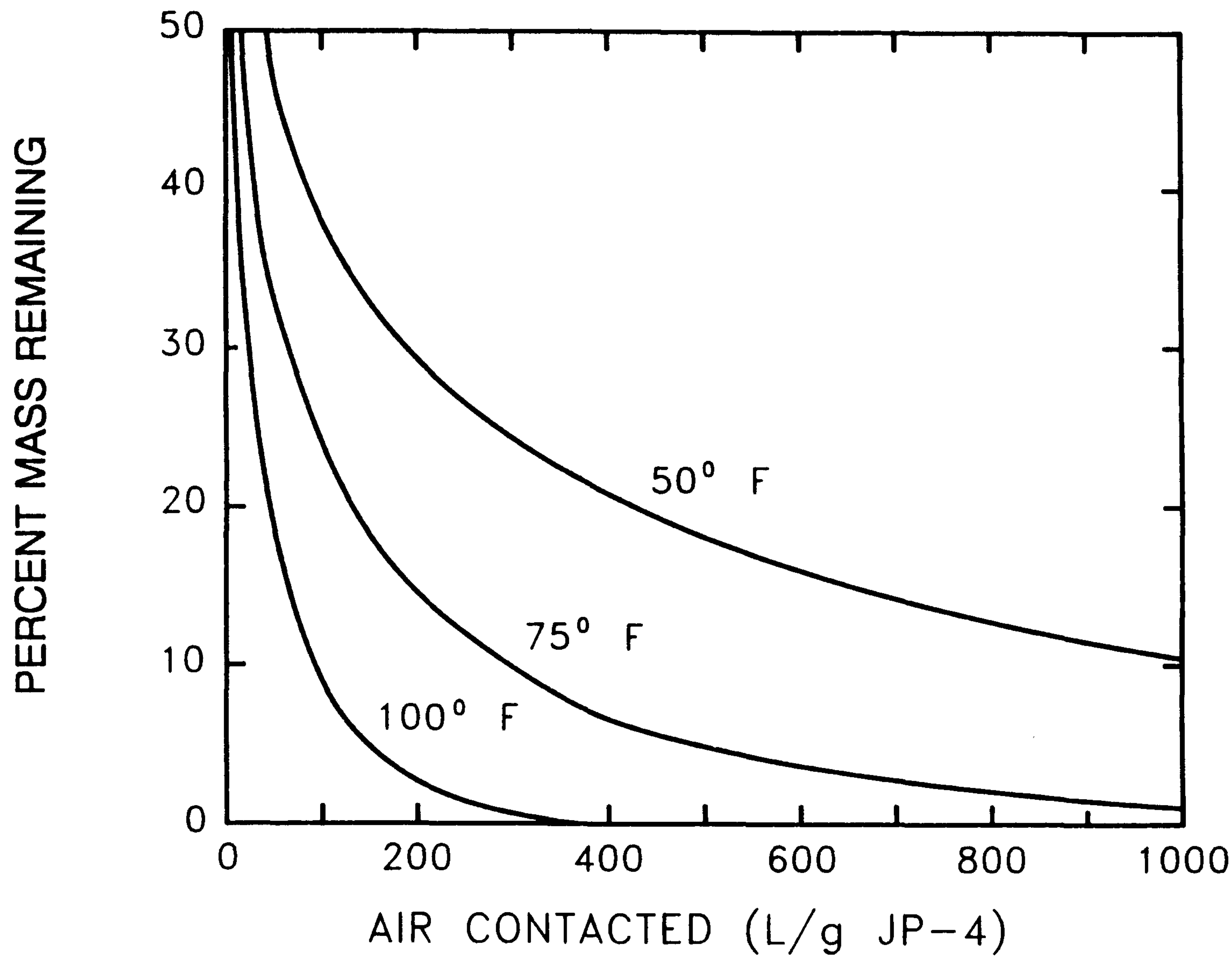


Figure 17. Equilibrium Removal Curves for JP-4 Showing the Effect of Temperature.

The economics of heat-enhanced soil venting are uncertain. One could calculate the cost of operation of blowers and emissions control using an equilibrium model for the off-gas concentration and removal schedule, but unknowns would be the energy input necessary to achieve and maintain a given temperature and the homogeneity of heating.

The Hill AFB demonstration of heat-enhanced venting used passive injection of catalytic incinerator stack gas during a seven-week test. Details of this test are given in Volume III. Despite shortcomings of the test, which include limited heat input and uneven heating due to air flow distribution, a measurable enhancement of removal due to heating was detected. The results indicate that a system designed with a more uniform flow field for more even heating could remediate a site several times faster than an unheated case (up to 6 times faster for the conditions of the test). Although the test results cannot be used to universally prove or disprove the economic advantages of the approach, in general, the concept of heat injection appears attractive when waste heat is readily available. Heat enhancement will become more economical for systems with higher operating costs, such as sites with soils of low air permeability or costly emissions control.

Further work in this area, including heat and contaminant transport modelling and long-term field demonstrations, is urged for further illustration of advantages of the technique and to define ranges of site variables for which the technique is applicable.

5. Switching Emissions Control Options

The extracted gas contaminant concentrations will decrease over a large range during system operation, from levels over 100 percent LEL to below discharge limits. It is likely that a single emissions control technology will not be the most cost-effective throughout the operation. Since emissions control may be the most expensive part of the operation, switching emissions control devices at some point in the operation may result in relatively large savings.

As suggested by Johnson et al. (Reference 1), four emissions control technologies most likely to be used are thermal oxidation or flaring, catalytic oxidation, activated carbon adsorption, and dispersion stacks. Recommended economical ranges of operation were greater than 10,000 ppmv total hydrocarbons for thermal oxidation, less than 8000 ppmv for catalytic oxidation, and total removal rates of less than 100 grams/day for carbon adsorption. Heat recovery or dilution will likely extend the range of economical operation of the oxidation systems as shown in the successful operation of catalytic oxidation units during the entire Hill AFB demonstration. Direct discharge through dispersion stacks is regulated by discharge limits.

To estimate the time at which switching emissions control options would be economical, estimates of the variation in off-gas contaminant concentration with time and the cost of emissions control operation as a function of contaminant concentration are necessary. Also necessary is consideration of time and cost required for regulatory approval of the modified air emissions permit.

If several sites are to be treated, it would be most cost-effective to design emissions control devices as transportable units. Emissions control units mounted on trailers containing necessary auxiliary equipment could be quickly exchanged and put into operation. The trailers could also be outfitted with knock-out drums, vacuum blowers, and control equipment for complete transportable soil venting systems. This approach would be particularly useful in tailoring systems for different portions of venting operations. For instance, equipment suited for high concentrations may be more costly, but may be needed for only a relatively short period of operation. A trailer-mounted start-up unit could be moved from site to site for handling of the most concentrated gases, distributing the cost over many operations.

6. Enhancement of Biodegradation

Soil venting is an efficient aeration technique which has been shown to be useful for enhancement of aerobic biodegradation. Measurements of biodegradation associated with the Hill AFB soil venting demonstration are presented in Volume III. Biodegradation is attractive since it is also effective on non-volatile compounds and no gaseous emissions requiring control are produced. It may be possible to optimize biodegradation relative to volatilization in order to reduce costs.

During early operation, volatilization rather than biodegradation is likely to be the primary means of removal due to the high concentrations of hydrocarbons in the extracted gas. As hydrocarbon concentrations decrease, emissions control costs per pound of hydrocarbon treated will increase. At some point, it may be advantageous to reduce extraction rates by extracting gas from perimeter wells while continuing aeration of the soil or by decreasing air flow. Biodegradation would then account for a greater portion of the hydrocarbon removal. The emissions control may be removed at this point if extraction of hydrocarbons is held below limits. It is not clear at what point this operational change would be made. The extracted gas hydrocarbon concentrations should be low enough so that at the allowable flow rate adequate oxygen influx for bioactivity would occur.

Biodegradation associated with soil venting is not yet well-understood and is currently under study in other Air Force-sponsored demonstrations.

C. TERMINATING OPERATION

A major concern in operating a soil venting system is determining when to terminate operation. The following section will discuss some points relevant to this topic. Section VI.C.1. will discuss closure limits and suggest techniques for correlating these limits to readily measured quantities. Section VI.C.2. describes methods which may be used to project the time necessary to reach the shutdown point.

1. Definition of the Shutdown Point

Throughout this report, we have used 80 percent removal of contaminants by volatilization as a projection of the shutdown point of the remediation system, with the remainder assumed to be removed by biodegradation. In practice, the point at which a venting system may be shut down to perform postventing certification (Section VI.D.1.) will be dictated by closure limits agreed upon between the operator and the regulators. This point is most commonly defined in terms of soil concentration limits of specific compounds, such as BTX, or total petroleum hydrocarbons. Other closure levels reported have been in terms of soil gas levels or groundwater equilibration potential based on extracted gas concentration levels (Reference 48). This latter type of limit may be approached with much more certainty; that is, less costly tests may be required to prove cleanup. Soil sampling and analysis would be costly if it were necessary to repeat them several times.

Closure limits based on soil gas concentration could be proven by a very straightforward method. In this case, the venting system would be shut down for a specified time and allowed to equilibrate. Upon restart, the gas extracted would be analyzed for comparison to limits. If limits are based on groundwater equilibration levels or upon soil concentration, bench testing would be helpful for determining the extracted gas concentration at which treatment to closure levels can be expected.

When trying to determine whether soil gas levels have fallen to the point at which compliance testing could be undertaken, make sure to allow sufficient reequilibration times before measuring soil gas concentrations. This is due to diffusional effects in the soil, as pointed out by Payne (Reference 49) and Silka (Reference 50).

2. Projection of System Behavior

Projection of contaminant removal by venting is a very uncertain undertaking. A few techniques may be attempted, such as extrapolations of system behavior, simple equilibrium models, or more complex numerical models. These methods would allow one to predict the time it will take to reach a given extracted gas concentration.

Extrapolations of behavior may be made by plotting the contaminant concentration as a function of the cumulative amount of gas extracted. In some cases semi-log and log-log plots of contaminant concentration vs cumulative gas extracted have been reasonably successful in producing straight lines (see Volume I).

Equilibrium models, such as the one described in Appendix B, may be more successful in many cases, such as shown for the Hill Air Force Base demonstration. For cases where equilibrium does not control removal, an efficiency factor may be used. Estimation of and the use of the efficiency factor is described in Section V.B.3.

More complicated models which include multiple mechanisms and coupled air flow and contaminant transport could be conceived to handle all cases. At this point, further model development and validation are necessary to produce a general tool which may be applied by users to project removal behavior at any site.

D. POST OPERATION ACTIVITIES

Following completion of venting, activities remaining include; demonstration of the effectiveness of remediation in complying with regulatory guidelines, decommissioning of all equipment, and proper disposal of any residual wastes.

1. Demonstration of Effectiveness of Remediation

Following the venting operation, the site must be certified as "clean" if the remediation has been driven by regulations. The plan for certification of remediation effectiveness will have been described as part of the Work Plan proposed to the appropriate regulatory agency prior to initiation of the venting operation. Post-venting certification sampling may be required to demonstrate effectiveness of remediation. Certification may be based on: (1) reduction of vented air VOC concentrations to a negotiated level; (2) reduction of groundwater VOC concentrations to a regulatory action level; or (3) reduction of residual soil concentrations to a negotiated or regulatory action level.

a. Groundwater Analysis

When soil contamination has resulted in groundwater contamination, sampling of the groundwater may show that the groundwater is no longer being impacted by the overlying contamination. Regulatory action levels for water exist for many of the more common VOCs likely to be amenable to soil venting. The number of samples collected and time interval between collection would need to be defined in the post-venting sampling plan and approved by the regulators. Three separate sample collections at intervals of one week are commonly used in groundwater sampling programs to confirm absence of contamination above action levels.

An alternate procedure which has been proposed by Payne et al. (Reference 48) involves inferring contamination levels in groundwater by dividing the vented air concentration, measured at some period of time after shutdown of venting operation, by the Henry's Law coefficient obtained from the literature. This method is based on the assumption that after a period of time without air movement, air and water contaminant concentrations return to equilibrium in the subsurface.

b. Soil Analysis

Direct sampling of the soil may be required by the state regulatory body if sufficient VOC soil contamination levels exist. Post-venting soil sampling involves installing borings throughout the contamination zone, and collecting and analyzing soil samples according to methods approved by the regulatory agency. If preliminary sampling was conducted (Section III.B.), post-venting sampling should utilize the same methods.

An excellent discussion of statistical considerations and strategies for sampling of hazardous waste is found in USEPA (Reference 26). This discussion is primarily oriented toward homogeneous wastes, but the additional problems which occur in a three-dimensional non-uniform matrix, such as occurs in a volume of contaminated soil, are addressed in several examples.

The primary criterion for acceptance of a waste (or, by analogy, vented soil) promulgated by USEPA (Reference 26) is that the 80-percent confidence interval of the mean of a set of sample analyses must fall below the regulatory action level for the waste to be certified as non-hazardous. Generally, some form of random sampling is recommended; as more is known about the distribution of characteristics of the waste (i.e., soil), the sampling plan may employ greater subdivision of zones to achieve greater homogeneity within each zone. Thus, in soil venting in which exploratory borings have been installed, vertical zones may be defined on the basis of soil type (sand, clay, etc.) within the vented zone.

A typical sampling plan might call for installation of several borings at random locations across the vented area. USEPA (Reference 26) details several methods for selecting the locations for boring. The number of borings is determined by the tradeoff between the cost of boring and sampling, and the increase in precision of the mean contaminant concentration expected with an increased number of sampling points. Samples would then be collected at depths within each soil zone, also preselected randomly, and analyzed for VOCs. Contaminant concentrations determined for each soil zone would be averaged, and the mean concentrations related to the action level. If the upper 80 percent confidence level of the mean concentration falls below the action level, remediation is completed.

Because of the heterogeneity of soil, contaminant concentrations may vary widely following venting. High variability of residual contaminant levels could result in inability of postventing sample analysis to confirm contaminant removal to meet regulatory requirements. As pointed out in Section II.B.2.b.2., compliance with soil-based residual levels may be very difficult.

If a post-venting soil sampling program is required, venting should be continued for a sufficiently long period to provide a measure of confidence that residual levels are well below action levels. If initial soil VOC levels are known, the ratio of final vapor concentration to the initial vapor concentration may be used to estimate the mean reduction in soil VOC levels. To warrant ceasing operations and beginning postventing sampling, a "safety factor" should be employed to continue venting until the expected mean soil VOC level has been reduced to a sufficiently small fraction of the action level.

2. Decommissioning

Above-ground equipment will require disassembly and removal from the site. Final disposition of vent wells will require compliance with appropriate regulatory agencies. Because vent wells furnish a route for contaminant transport directly into the subsurface or potentially to groundwater, the prudent course of action is to remove them and backfill the borings to the surface. Backfill material may be bentonite grout, cement, clean soil, or sand; grout should be used at least below the water table. Any wastes remaining from vent well decommissioning or other site activities should be disposed of in accordance with regulatory guidelines.

SECTION VII

ECONOMIC ANALYSIS

A. INTRODUCTION

As indicated in Section II.B.1, the total costs of ISSV applications are site-specific and will vary depending on several factors. Many of the costs, such as site characterization, permitting, vent installation, and confirmatory sampling, may only be estimated on a case-by-case basis. This section provides estimates and analyses of those costs common to all ISSV applications for which capital and operating cost data are needed. Included are capital and operating costs for blowers and emissions controls, which are the primary above-ground equipment items that contribute to the capital cost. These estimates may be used to guide design strategy and equipment selection.

A spreadsheet-based econometric model was developed to provide the soil venting cost estimates. This model contains all the logic necessary for providing project lifetime financial analysis. The cost estimation procedures used are in agreement with guidelines of the United States General Accounting Office (GAO). This section summarizes the results from economic analyses of ISSV using the model. The econometric model provides economic analyses for three system configurations; (1) ISSV with no emissions control, (2) ISSV with off-gas treatment using catalytic oxidation, and (3) ISSV with off-gas treatment using activated carbon adsorption.

A schematic outlining this cost-estimating model is shown in Figure 18. The three main elements which provide input to the spreadsheet are (1) a contaminant removal model, (2) an air flow model, and (3) cost estimation algorithms. The contaminant removal model and the air flow model, which are described in other sections of this report, include simplifications and idealizations which convert the myriad field condition possibilities into a tractable problem. The contaminant removal model allows estimation of the concentration of contaminant in the extracted soil gas and the amount of removal as functions of time, and the air flow model provides a relationship of flow rate to vacuum required for the purpose of estimating power requirements. The capital and expense cost estimating relations for blowers and emissions control are based upon well-established techniques used in chemical engineering design. These capital and expense costs are used for the lifetime financial analysis to produce a value for the cost per pound of contaminant removed by ISSV.

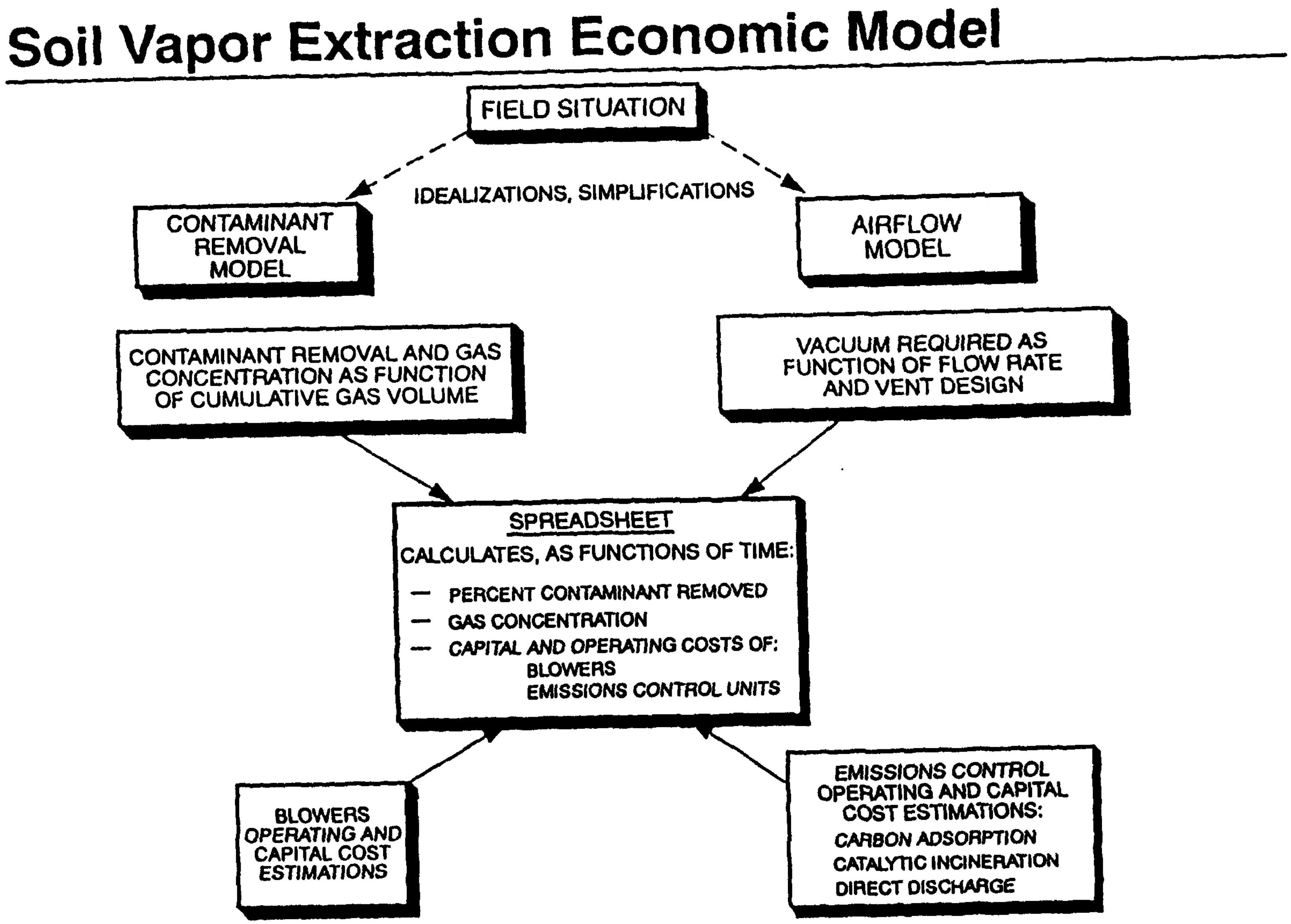


Figure 18. Soil Vapor Extraction Economic Model.

For documentation purposes, the spreadsheet-based econometric model is described in detail in Appendix F. Also, a guide to using the spreadsheet for cost estimating purposes is presented in Appendix G. Copies of the spreadsheet are available from Chemical/Physical Treatment Technologies Area Manger, HQ AFESC/RDVW, Tyndall AFB, Florida. Provide a blank diskette with your request.

B. ELEMENTS OF ECONOMETRIC MODEL

The primary input variables to the model include hydrocarbon spill size and physicochemical characteristics, percentage of the spill to be recovered, total time for cleanup, and the induced flow rate, which is determined by the total volume of air and the total time required for cleanup. Secondary input variables include vacuum requirements at the vacuum blower intake, percentage of heat recovery from the catalytic oxidation unit discharge (if oxidation is the emission control option), various mechanical efficiencies, interest rate, inflation rate, various utility rates, overhead costs, and annual operating load factor (fraction of year that equipment can be expected to be on-line).

Fuel or solvent spills can cover a broad range of hydrocarbon components. For the analyses in this manual, the spilled components are assumed to have the characteristics of a "weathered" JP-4 composition that was derived from field samples taken during the Hill AFB demonstration.

Important features of the cost-estimating model include the following:

- The capital costs of major equipment items were calculated from correlations, some of which are from the literature and some derived from the Hill AFB demonstration.
- Factors from the literature were used for equipment installation costs and were adjusted upward slightly to allow for a moderate amount of site preparation.
- For the two cases of ISSV with no off-gas treatment and ISSV with off-gas treatment by catalytic oxidation, annual maintenance is calculated at 10 percent of initial fixed capital costs—this somewhat high value was used as a surrogate for periodic total replacement of the blower system. This is because it is not expected to have single-site operating lifetimes greater than five or six years. For the case of ISSV with carbon adsorption for emissions control, annual maintenance is calculated at 1 percent. Because of the relatively high capital cost for carbon treatment, a 10 percent value would produce an unrealistically high maintenance cost.
- Labor was set at 0.25 full-time equivalent and a 1990 full-time annual salary of $24,000.
- Indirect costs (overhead) were set at a percentage of total direct expense (non-capital costs), exclusive of interest on debt (in the case of carbon adsorption, the very high cost component for carbon regeneration is excluded from the overhead base).
- An average annual inflation of 4.84 percent was used to adjust costs to 1990 dollars.

- The applied interest rate was the sum of the inflation and the real interest rates—an average value of 5 percent was used for the real interest rate which is consistent with the current state of the national economy and with recent practices in studies performed for the U.S. GAO (References 50-54).
- Fixed capital costs are depreciated linearly over a 10-year period, with zero salvage value.
- All cost estimates are given in thousands of 1990 dollars.
- The base for the lifetime financial analyses is the current year dollar cost per pound of spill cleaned up; e.g., cost for 1995 operations would include estimates of the effect of inflation.
- The capital and expense cost estimating and lifetime financial analyses deal only with the surface vent operations, and do not include any allowances for drilling vent wells, installing well casings, installing air collection headers, etc.
- The carbon adsorption capacity was 0.25 grams JP-4 per gram carbon.

The PC-based (personal computer) spreadsheet model prepared for these economic analyses is in MS MULTIPLAN, version 2.01 format. The spreadsheet may be exported upward into MULTIPLAN versions 3.0 and 4.0, and into MS EXCEL. MULTIPLAN was selected because of its capability to automatically perform iterative calculations (required, for example, when there are circular dependencies between different cells of the spreadsheet).

C. ILLUSTRATIVE RESULTS

Results of example calculations are presented for application of soil vapor extraction to spills of JP-4 jet fuel. In these calculations, it was assumed that the operation termination point would be the point that the equilibrium model predicted 80 weight percent removal of the fuel by volatilization. This design removal value was considered reasonable for JP-4 for two reasons. First, JP-4 contains heavy fractions that are difficult to remove by volatilization. These heavy fractions are less likely to be transported in the soil, and therefore pose less of a hazard than some of the more volatile and mobile compounds, such as benzene. Secondly, biodegradation is likely to aid in the removal of the hydrocarbons, including the heavy fractions. Biodegradation rates during the Hill AFB demonstration were on the order of 15-20 percent of the volatilization rate. It is expected that other sites will provide conditions for bioactivity as good or better than those in this demonstration. The actual termination point in practice will be dictated by applicable regulations.

As mentioned above, the input to the contaminant removal model was a weathered fuel composition derived from field samples taken during the Hill AFB demonstration in order to provide conservative values for schedule and cost and to somewhat offset the non-idealities present in field

implementations. Output of the equilibrium contaminant removal model indicates that this fuel composition requires a gas volume 2.6 times larger than the volume required for a JP-4 standard sample to reach the termination point.

The usefulness of this model may be seen from the simulation results shown in Figures 19 and 20. These figures show the total cost per pound of contaminant removed for operation of blowers and emissions control devices as a function of the total amount of time needed for the desired level of cleanup. Because of the equilibrium assumption, the extracted gas flow rate is inversely proportional to cleanup time. The curves correspond to conditions with a constant applied vacuum of 100 inches (25 Pa) of water regardless of flow rate (for this to occur, the number of vents operated would be varied as a function of soil permeability and flow rate). Figure 19 shows the results obtained for an initial JP-4 spill size of 1000 gallons (3.8 m^3), and Figure 20 shows the results for a JP-4 spill of 50,000 gallons (190 m^3). From these plots, the following observations may be made; (1) emissions control may add greatly to the cost of application of soil vapor extraction and (2) except for short cleanup times for the larger spill, carbon adsorption is more expensive than catalytic oxidation in this example. Due to the economy of scale, the cost per mass of contaminant removed is less for larger spills than for smaller spills.

The results of calculations for various spill sizes, ranging from 100 to 50,000 gallons, and cleanup times of 1, 2, 4, 10, and 20 quarters (0.25-5.0 years) are presented in Tables 8-10. The costs, in dollars per pound of contaminant removed, are given for the capital items and the expense items separately. From these tables, the expense items are seen to be the major contributor to the total clean-up cost. This is due in part to the application of overhead and to the depreciation of the capital costs over a 10-year lifetime. These parameters may be varied in the spreadsheet to determine their effects on the total cost. It should be noted that at long cleanup times and small spill sizes, the results become questionable due to the small equipment sizes required at the low air flow rates.

It is reemphasized that any of the input parameters to the spreadsheets may be varied from the values used to generate the results presented in this section. As one gains experience with the operation and the costs of ISSV, the input parameters can be changed to provide more accurate cost estimates. This also applies to other features of the econometric model, such as the cost correlation equations and the contaminant removal model.

As an example of the effect of the input parameters, for the case of carbon adsorption as emissions control, calculations were also made for carbon capacities of 0.35 and 0.15 grams per gram of carbon for a spill size of 25,000 gallons of JP-4. The corresponding lifetime operating costs for

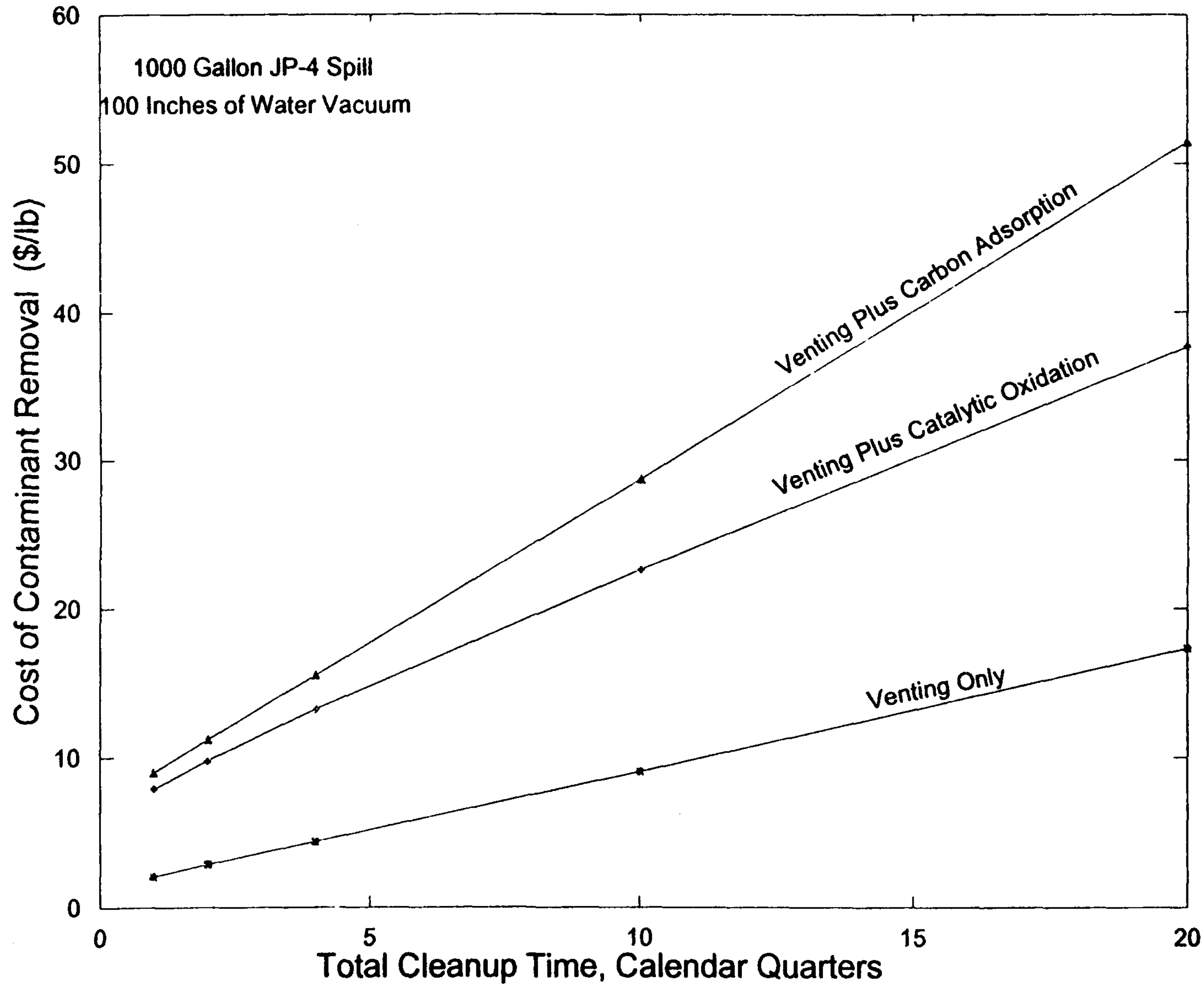


Figure 19. Variation of Total Processing Cost with Total Cleanup Time at a Constant Vacuum of 100 inches H_2O; 1000 Gallons JP-4 Jet Fuel Spill Case.

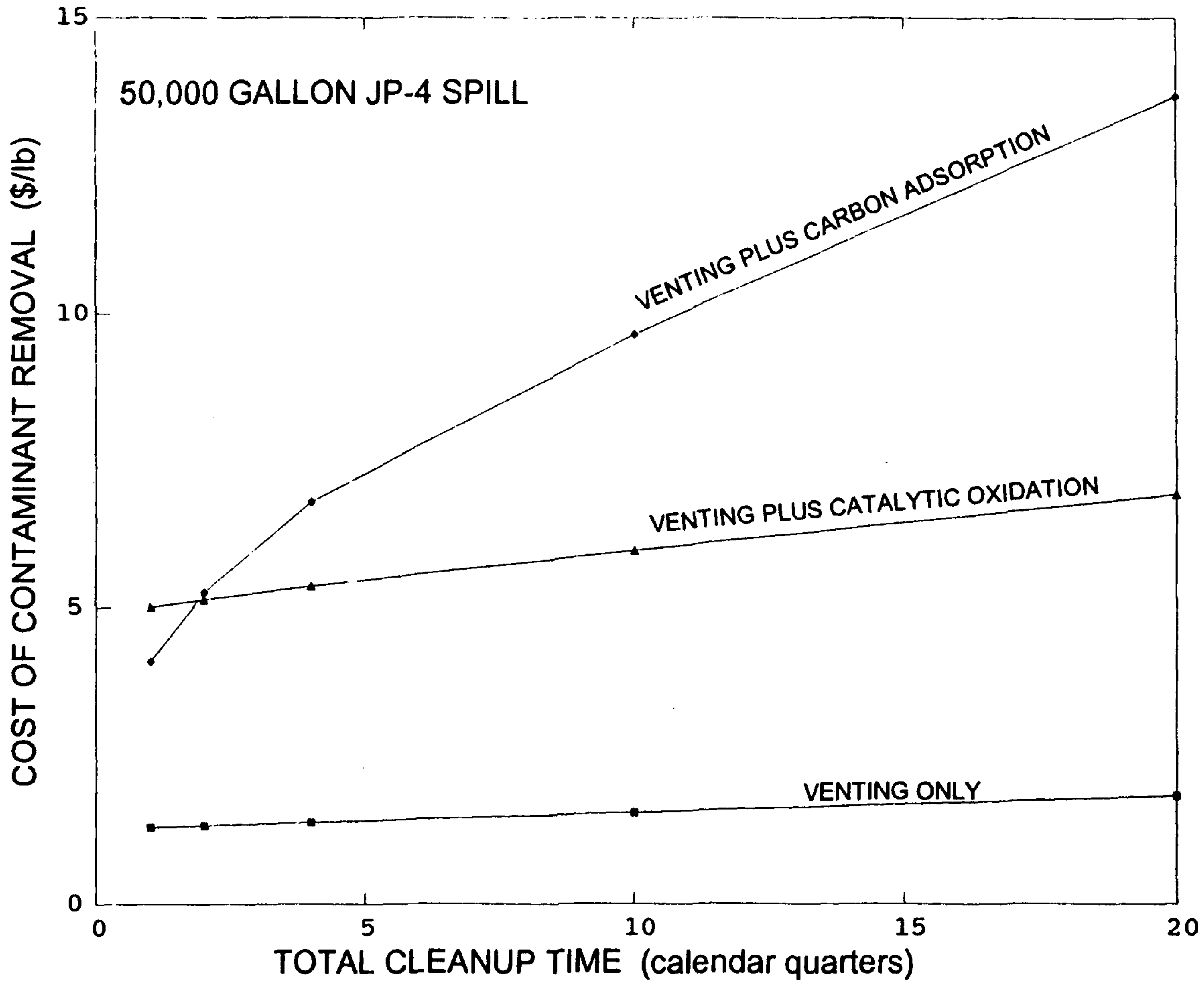


Figure 20. Variation of Total Processing Cost with Total Cleanup Time at a Constant Vacuum of 100 inches H_2O; 50,000 Gallons JP-4 Jet Fuel Spill Case.

TABLE 8. CLEANUP COSTS PER POUND OF CONTAMINANT (SOIL VENTING ONLY) (CURRENT YEAR DOLLARS/POUND CLEANED UP)

SPILL SIZE (gal)		CLEANUP TIME (QUARTERS)				
		1	2	4	10	20
100 (451)[a]	Expense	8.404	15.153	28.745	70.945	147.561
	Capital	0.356	0.593	0.988	1.94	3.231
	TOTAL	8.76	15.746	29.733	72.885	150.792
500 (2262)	Expense	2.798	4.208	7.034	15.757	31.513
	Capital	0.109	0.181	0.302	0.593	0.987
	TOTAL	2.907	4.389	7.336	16.35	32.5
1000 (4524)	Expense	2.062	2.788	4.236	8.697	16.722
	Capital	0.065	0.109	0.181	0.356	0.593
	TOTAL	2.127	2.897	4.417	9.053	17.315
5000 (22618)	Expense	1.445	1.606	1.926	2.902	4.644
	Capital	0.02	0.033	0.055	0.109	0.181
	TOTAL	1.465	1.639	1.981	3.011	4.825
10000 (45237)	Expense	1.361	1.449	1.621	2.146	3.08
	Capital	0.012	0.02	0.033	0.065	0.109
	TOTAL	1.373	1.469	1.654	2.211	3.189
25000 (113092)	Expense	1.308	1.349	1.431	1.678	2.115
	Capital	0.006	0.01	0.017	0.033	0.055
	TOTAL	1.314	1.359	1.448	1.711	2.17
50000 (226183)	Expense	1.289	1.314	1.364	1.516	1.782
	Capital	0.004	0.006	0.01	0.02	0.033
	TOTAL	1.293	1.32	1.374	1.536	1.815

[a]Gives pounds removed during cleanup.

TABLE 9. CLEANUP COSTS PER POUND OF CONTAMINANT (VENTING PLUS CATALYTIC OXIDATION) (CURRENT YEAR DOLLARS/POUND CLEANED UP)

SPILL SIZE (gal)		CLEANUP TIME (QUARTERS)				
		1	2	4	10	20
100 (452)*	Expense	19.542	29.783	49.422	106.962	206.287
	Capital	3.678	6.014	9.842	18.898	30.987
	TOTAL	23.22	35.797	59.264	125.86	237.274
500 (2262)	Expense	8.851	11.41	16.219	29.956	53.155
	Capital	1.177	1.921	3.138	6.009	9.834
	TOTAL	10.028	13.331	19.357	35.965	62.989
1000 (4524)	Expense	7.177	8.621	11.31	18.907	31.6
	Capital	0.722	1.177	1.921	3.675	6.009
	TOTAL	7.899	9.798	13.231	22.582	37.609
5000 (22618)	Expense	5.534	5.948	6.705	8.797	12.217
	Capital	0.233	0.379	0.617	1.177	1.921
	TOTAL	5.767	6.327	7.322	9.974	14.138
10000 (45237)	Expense	5.258	5.511	5.973	7.24	9.303
	Capital	0.143	0.233	0.379	0.722	1.177
	TOTAL	5.401	5.744	6.352	7.962	10.48
25000 (113092)	Expense	5.056	5.197	5.453	6.16	7.309
	Capital	0.075	0.122	0.199	0.379	0.617
	TOTAL	5.131	5.319	5.652	6.539	7.926
50000 (226183)	Expense	4.971	5.068	5.244	5.732	6.532
	Capital	0.046	0.075	0.122	0.233	0.379
	TOTAL	5.017	5.143	5.366	5.965	6.911

*Gives pounds removed during cleanup.

TABLE 10. CLEANUP COSTS PER POUND OF CONTAMINANT (VENTING PLUS CARBON ADSORPTION) (CURRENT YEAR DOLLARS/POUND CLEANED UP)

SPILL SIZE (gal)		CLEANUP TIME (QUARTERS)				
		1	2	4	10	20
100 (452)[a]	Expense	21.012	31.971	54.076	122.703	246.287
	Capital	7.23	14.341	28.485	70.681	140.715
	TOTAL	28.242	46.312	82.561	193.384	387.002
500 (2262)	Expense	9.596	11.984	16.747	31.45	57.825
	Capital	1.622	3.208	6.355	15.727	31.256
	TOTAL	11.218	15.192	23.102	47.177	89.081
1000 (4524)	Expense	8.087	9.41	11.987	19.878	33.986
	Capital	0.909	1.797	3.558	8.797	17.474
	TOTAL	8.996	11.207	15.545	28.675	51.46
5000 (22618)	Expense	6.482	7.113	8.007	10.436	14.646
	Capital	0.329	0.65	1.29	3.195	6.353
	TOTAL	6.811	7.763	9.297	13.631	20.999
10000 (45237)	Expense	5.87	6.589	7.372	9.174	12.146
	Capital	0.254	0.503	1	2.482	4.943
	TOTAL	6.124	7.092	8.372	11.656	17.089
25000 (113092)	Expense	4.754	5.757	6.686	8.265	10.546
	Capital	0.208	0.413	0.823	2.048	4.086
	TOTAL	4.962	6.17	7.509	10.313	14.632
50000 (226183)	Expense	3.911	4.879	6.029	7.747	9.884
	Capital	0.192	0.382	0.763	1.901	3.796
	TOTAL	4.103	5.261	6.792	9.648	13.68

[a]Gives pounds removed during cleanup.

a cleanup time of 5 years were $11.50 and $22.10 per pound of spill removed, respectively. This compares to $7.93 per pound for catalytic oxidation as the emission control. The carbon capacity parameter, as would be expected, significantly affects the costs for carbon adsorption. Experimental or actual operating data for carbon capacity for JP-4 components would be desirable to more accurately predict costs for emission control by carbon adsorption.

Another parameter that significantly affects the economics of the carbon adsorption emissions control option is the average carbon recycle interval (expressed as a fraction of the total cleanup time). A value of 0.1, which was used in these illustrative calculations, means that the carbon bed is regenerated ten times during the cleanup period, regardless of the length of the period. If a greater value for this fraction is input to the model, the carbon bed is regenerated fewer times, but the size of the bed, and consequently the capital cost, increases. Conversely, as the value for the fraction is decreased, the bed is regenerated more times and the required bed size decreases. While this would appear to be desirable, because of the decrease in capital costs, a point would be reached at which the number of bed regenerations would become impractical and/or noneconomic because of the manpower requirements. The economic model assumed labor to be 0.25 FTE and does not take into account increased labor costs due to numerous carbon bed regenerations.

In general, if vacuum requirements are not important (such as for very permeable soils or many operating vents), the cost per mass of contaminant removed is less for shorter cleanup times. However, in most cases the vacuum required to induce the higher flow rates for shorter cleanup times leads to higher blower costs, and, thus, there should exist an extraction flow rate for which the cost per mass removed is a minimum for each application. This prediction of particular flow rate leading to a minimum cost may be seen in Figure 21. In this figure, the costs for extraction alone, extraction with catalytic oxidation, and extraction with carbon adsorption are plotted as functions of both cleanup time (related to flow rate) and the number of operating extraction vents for a field situation similar to the Hill AFB demonstration. Rather than assuming a constant applied vacuum as in the above cases, the vacuum required was calculated as a function of the number of vents and flow rate using Equation (25). For these calculations, a 25,000 gallon (94.6 m^3) JP-4 spill was assumed, the extraction vent radius was four inches (0.1 meter) and the screened section length was 40 feet (12.2 meter), the air permeability of the soil was 2.8×10^{-7} cm^2 (2.8×10^{-11} m^2), the area of contamination was 12,500 ft^2 (1160 m^2), and the average initial contaminant concentration in the soil was 4300 g/m^3. To produce an upper estimate of the vacuum requirements, the removal factor RF was 1000 liters of air/gram of JP-4 (1.0 m^3/gram), corresponding to the 80% removal point for volatilization of the weathered fuel composition. The air was assumed to be at 60°F (15.5°C) and 1 atm, so that μ = 0.044 pound/foot·hour (1.82×10^{-5} Pa·s).

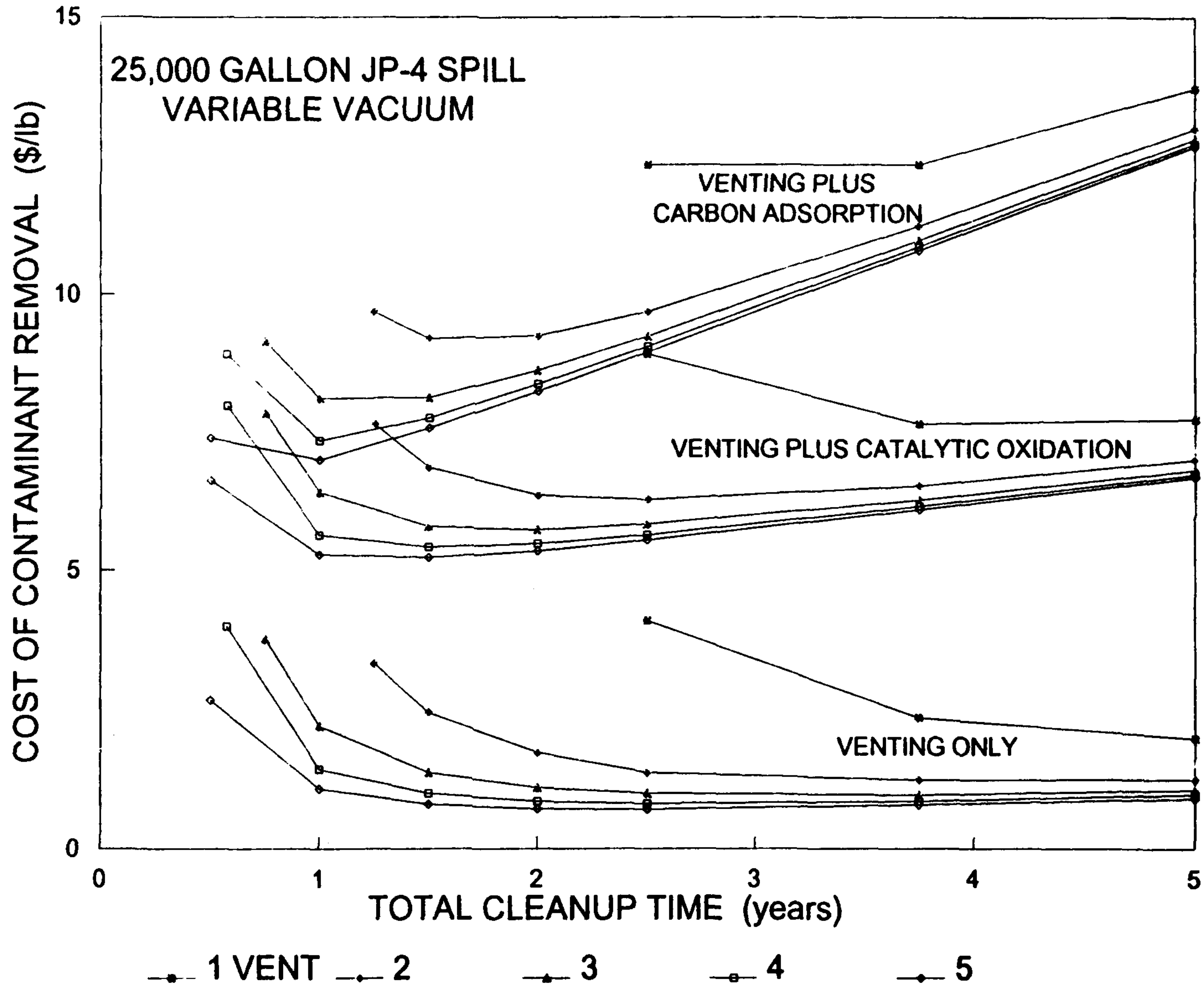


Figure 21. Variation of Total Processing Cost with Total Clean Up Time and Number of Vents Including Variable Vacuum for 25,000 Gallons JP-4 Jet Fuel Spill Case.

The cost curves in Figure 21 terminate on the left end at the cleanup time which causes a vacuum requirement of 200 inches of water; thus it is seen how blower capabilities affect the achievable range of cleanup times. In general, as more vents are operated, less suction is required to induce the required flow rate, leading to less expensive operation. This trend will continue until the cost of vents (not included in this analysis because it will be site-specific) becomes prohibitive. The marginal cost advantage of each additional vent is lower for a greater numbers of vents, so there will also be an economic minimum in the number of vents.

Due to the relative cost of emissions control and blowers, the flow rate leading to a minimum cost is greater (or cleanup time is shorter) in the cases including emissions control than for the case with extraction only. As seen in Figure 21, the minimum cost for the case of no emissions control with multiple vents occurs from about 2 to 2.5 years. With emissions control, the minimum costs occur in the range of 1 to 2 years for multiple vents.

The value of such modeling for technology selection and conceptual design of a soil vapor extraction system is evident. It is apparent (and expected) that it is economically preferable not to have emissions control unless required. If emissions control is required, the most cost-effective technology may then be chosen. For the example case, catalytic oxidation would be chosen over carbon adsorption. The model would also provide input into sizing of blowers and emissions control units by estimating the flow rate that gives the lowest total remediation cost. Having selected a system size, an estimate of the total cleanup time is possible.

Undoubtedly, there are great uncertainties in the application of this or any other *in situ* technique and in the models that are used to simulate them. Detailed study of a particular application would necessarily follow the application of the simple model presented here to get better guidance for implementation of the technology.

D. CONCLUSIONS OF ECONOMETRIC MODELLING

A model for estimation of operating time and cost for many applications of soil vapor extraction has been developed. The model is spreadsheet based and readily implemented on a personal computer. This model approach should be quite valuable during the process of remediation technology selection, and may be very helpful in process design. The model is the result of many simplifications and idealizations, and thus its limitations should be kept in mind. Major deviations from the behavior predicted by this model would be expected when diffusive mass transport is important, such as in cases of free product on groundwater or of contamination zones comprised of less permeable material in more permeable soil. An efficiency term may be successful in reducing deviations in these cases.

The example cases run for JP-4 jet fuel show that there is an economy of scale in the application of the technology, with lower cost per mass removed for larger spills. Emissions control adds considerably to the cost. Rough estimates of the cost of carbon adsorption show it to be more expensive in most cases. Carbon adsorption is thus only recommended for the smallest spills, where it may be implemented much more easily. In the example cases, catalytic oxidation was cheaper than carbon adsorption, with direct discharge to the atmosphere being the cheapest. For each system, when vacuum requirements are taken into account, there is a flow rate that corresponds to a minimum remediation cost, indicating that more detailed analysis of particular situations should yield optimum system design.

Further refinements of this approach, leading toward a technique for system optimization, should include a more detailed model of carbon adsorption and a contaminant removal model that couples contaminant transport and subsurface air flow patterns and that also takes diffusive mass transport into account. With such a removal model, contaminant removal rate would become a function of flow rate; thus, the total process cost would become a more complicated function of flow rate, contaminant distribution, geohydrology, and the emissions control option. As greater efforts are made to have models approach reality in soil vapor extraction, the models will become more complicated to implement and thus may lose some appeal; in particular, time and budget constraints may limit the application of such models to field situations. A single model, as outlined here, would then be valuable for initial purposes, with a more complex model applied during detailed system design.

SECTION VIII

CONCLUSIONS AND RECOMMENDATIONS

In situ soil venting is an effective and potentially cost-effective technique which should be considered for the remediation of volatile contaminant spills. However, due to limited documented field work, the uncertainty involved in and lack of development of predictive models, and the site-specific nature of the technique, an explicit design procedure cannot be defined. This manual has discussed each aspect of implementation to provide guidance in selecting and applying the technology. The main points to consider are listed below.

It is imperative that reliable and complete site characterization data are obtained. Data of particular interest in the selection and design of soil venting include the composition and concentration of contaminants, depth and areal distribution of contaminants, soil stratigraphy, soil moisture content, depth to groundwater, and air permeability of the soil. Of these, the single most important design variable is air permeability of the soil, which is frequently not measured in site characterizations. Section III.C. of this manual describes simple *in situ* tests which can be conducted to provide rapid, inexpensive, and accurate measurements of air permeability.

The selection of soil venting, or any other remediation technology, must be based upon technical, economic, and political issues. Technical issues to be considered in the suitability of soil venting include contaminant volatility, air permeability of the soil, size and depth of spill with respect to capabilities of excavation, and complexity of soil stratigraphy and geohydrology. Other issues to be considered are cost and legal implications, including patent issues and regulatory requirements. A conceptual design as developed in Section IV and Appendix C may be used in conjunction with the econometric model presented in Section VII and Appendices F and G to provide cost estimates for comparison with other potential treatment processes.

Although the conceptual design of Section IV will provide an educated start toward system design, a pilot test should be conducted prior to full-scale design and implementation. Data to be obtained during the pilot test will include air permeability estimates and contaminant removal rates. It is recommended that the pilot test be operated long enough that gas concentrations are significantly lowered and a shutdown and restart be conducted to estimate the importance of diffusion control upon contaminant removal.

In most cases, the information from the site characterization and pilot test will be used to design a full-scale system using approximate methods which have their basis in radial flow and equilibrium removal assumptions. However, advances are being made in modelling of coupled air flow and contaminant transport which will be useful in system design and optimization. When applying such models, one must recognize the limitations imposed both by the assumptions made by the transport equations in the model and the uncertainty in the inputs to the model.

Full-scale system design defines the number, placement, and construction of vents, the type and layout of piping, size and design of vapor/liquid separator, vacuum and flow capacity of a given type of blower, and emissions control type and size. Other equipment necessary are safety equipment such as flame arrestors and explosive gas detectors, pressure/vacuum gauges, flowmeters, and vapor analyzers.

In general, well-designed soil venting systems may be operated with limited long-term manpower requirements. A system should be operated with the general strategy to continually maximize the extracted gas contaminant concentration. Such a strategy involves periodic adjustment of operating conditions, thus will require a certain degree of attention and documentation of system operation history. Shutdown of soil venting operations is contingent upon meeting regulatory requirements; it is important to have shutdown criteria defined in advance.

As mentioned throughout this document, application of soil venting carries with it the uncertainties that are present in any environmental remediation, particularly *in situ* techniques. These uncertainties will impact scheduling, design, cost, and technology selection. Some of the uncertainties to consider include:

1. The amount of contaminant present at the site will not be known precisely due to soil and contaminant distribution heterogeneities. In fact, most people in this field agree that soil sampling is an art rather than a science and that a mass balance on a venting application is very likely to be in error. The impact of this point is that precise scheduling and budgeting will be impossible and assessment of progress toward a cleanup goal will be difficult.
2. Heterogeneities in the soil and contaminant distribution and possible multiple factors controlling removal make projection of removal via modelling an uncertain venture. Again, although modelling will improve predictions, scheduling and budgeting can only be made as order of magnitude estimates. Therefore, keep methods as "simple" as possible.
3. The *in situ* nature of the technology leads to the possibility of remaining patches of contamination in a seemingly otherwise treated site. The specific design of the confirmatory

sampling plan and data analysis procedures agreed upon by the site operator and regulators prior to venting operations may substantially affect the success of the venting operation in satisfying regulatory requirements for remediation.

ISSV is still a relatively new remediation technology with great room for improvements and additions to our knowledge through study of field applications. Listed below are major points in which improvements would benefit users of this technology:

1. A major point of doubt and controversy surrounding ISSV is the applicability of cleanup standards. The technique is undoubtedly one of the most effective means of remediation, yet regulatory standards based on statistical soil sampling with low compound-specific limits makes application of this or any other *in situ* technique less attractive. More reasonable closure standards based upon realistic risk assessment, such as the equilibrium groundwater concentration criteria met successfully by Payne and Lisiecki (Reference 48) or soil concentration limits based on total contaminant concentrations or averaged values would be more suitable for application of ISSV. Certainly, more standardized closure limits through guidance from the EPA would be welcome.
2. ISSV is still an unfamiliar technology to many regulators and potential users. The publication of the technical details of successful applications of this technology will be useful in informing the public of its potential and will provide a larger information base suitable for increased regulatory approval.
3. Improved models will be useful for better budgeting and scheduling of venting applications. Continued work needs to be performed in the laboratory to determine factors controlling removal under different soil, contaminant, and flow conditions, and in documented field applications from which data may be obtained for validation of models.
4. Improvements in cost-effectiveness of the technology may be foreseen by increasing removal rates through such methods as heat enhancement and by optimizing biodegradation during venting operations. Continued further testing of these and other enhancements of venting is urged.

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APPENDIX A

PATENT ISSUES ON *IN SITU* SOIL VENTING

This appendix contains the text of a letter, dated 10 August 1989, from Wayne A. Warner, Attorney Advisor, to RDVW (Captain Elliott) on the subject of "Patent Issues on *In Situ* Soil Venting."

1. This office has reviewed your letter dated 13 July 1989 in which the following questions were raised regarding the publishing of a Government Guidance Document on the design, construction, operation, and costs of *in situ* soil venting systems.

    a. If the base implements the technology without using an outside contract, does it need to hold a license from a patent holder?

    b. If a base uses a contractor to implement the technology, does the contractor need to purchase a license from the patent holder?

    c. If a base uses a contractor who does not have a license for the technology, could the Air Force be liable for any damages which might result from possible lawsuits by the patent holders?

    d. What procedures must a base follow to implement the technology and comply with the patent regulations? For example, how do we or the base determine which patent, if any, is applicable to its use of *in situ* soil venting technology.

2. The answers to the inquiries posed depend on how the particular patent involved was generated. If the patent resulted from federal financing, e.g., performance under a government R&D contract, then the Government will have, as a minimum, a nonexclusive, non-transferable, irrevocable, paid up license to practice, or have practiced for or on behalf of the Government, any subject invention throughout the world. Thus where a patent in which the Government has such rights is involved, the answers to the questions would be:

    a. The Government already has a license;

    b. No;

    c. No;

    d. Normal procedures where publication of guidance is concerned and where award of contracts is concerned. There is no need to determine which patents are applicable; if you know of any, identify them in your publication.

3. If a patent is involved in which the Government has no rights, the answers are altered to recognize that fact. In such a case the necessary responses would be:

   a. No. The Government may infringe a patent without fear of an injunction prohibiting such use; however, the Government would eventually be liable for damages, i.e., royalty payments to the patentee;

   b. The contractor does not need to purchase a license to perform a Government contract as once again injunctive relief is not available; however, the Government may eventually be liable for damages to the patentee. It may be advisable to acquire a license prior to a contract award in order to avoid an infringement suit later however. (See paragraph 4. below);

   c. Yes, unless a patent indemnity clause is used in the contract;

   d. Once again use normal publication and contracting procedures.

4. In those cases where the Government has authorized or consented to the manufacture or use of an invention described in and covered by a patent of the United States, any suit for infringement of the patent based on the manufacture or use of the invention by or for the United States by a contractor (including a subcontractor at any tier) can be maintained only against the Government in the U.S. Claims Court and not against the contractor or subcontractor (28 U.S.C. 1498). To ensure that work by a contractor or subcontractor under a Government contract may not be enjoined by reason of patent infringement, the Government shall give authorization and consent in accordance with the Federal Acquisition Regulations. *The liability of the Government for damages in any such suit against it may,* however, ultimately be borne by the contractor or subcontractor in accordance with the terms of any patent indemnity clause also included in the contract, and an authorization and consent clause does not detract from any patent indemnification commitment by the contractor or subcontractor. Therefore, both a patent indemnity clause and an authorization and consent clause may be included in the same contract.

5. In general, the following guidance pertains to patent use by or on behalf of the Government:

   a. The Government encourages the maximum practical commercial use of inventions made while performing Government contracts.

   b. Generally, the Government will not refuse to award a contract on the grounds that the prospective contractor may infringe a patent.

   c. Generally, the Government encourages the use of inventions in performing contracts and, by appropriate contract clauses, authorizes and consents to such use, even though the inventions may be covered by U.S. patents and indemnification against infringement may be appropriate.

   d. Generally, the Government should be indemnified against infringement of U.S. patents resulting from performing contracts when the supplies or services with relatively minor modifications.

6. With reference to your final question, we would like to emphasize that the patents issues raised really pose no problem if normal contracting procedures including the standard FAR patents clauses are used. Do not worry about determining which patents apply to your program; there are literally thousands of patents which could be infringed by *in situ* soil venting systems. If we may be of further assistance in this matter, please contact the undersigned at 882-5335 at your convenience.

/s/ WAYNE A. WARNER
Attorney Advisor

APPENDIX B

EQUILIBRIUM MODEL FOR PREDICTION OF VENTING BEHAVIOR

This section provides a description and directions for use of an equilibrium-based model of soil venting. The model was found to match the results of the Hill AFB demonstration quite well. This agreement lends credence to the results of the ISSV economic analyses for which the equilibrium model was utilized.

A. DESCRIPTION

The model presented herein assumes removal only by volatilization, ignoring the effects of biodegradation, aqueous solubility and volatilization from an aqueous phase or sorption on soil particles, such as was done by Johnson et al. (Reference 2). It also does not consider geometry of removal, as was presented in the two-dimensional Henry's Law-based model of Wilson et al. (Reference 37). Addition of these factors would not be difficult from a mathematical or computational standpoint for those experienced in numerical modelling; however, these additions would require the input of several adjustable parameters for which little information will be available and would require a longer program to be used. The program printed in this section may be input to a personal computer in a relatively short time.

This model is an idealized model based on Raoult's Law. Raoult's Law was chosen over Henry's Law for application to most fuel spills due to the low aqueous solubility of most fuel components (Henry's Law is valid for vapor-liquid equilibrium of one component at infinite dilution in another, as would be the case for hydrocarbons in aqueous solution; whereas Raoult's Law describes vapor-liquid equilibrium for an ideal solution of components, as is approximated by a mixture of similar hydrocarbons in a separate phase). This model assumes vapor-liquid equilibrium between a separate hydrocarbon phase and the soil gas, and perfect contact between the hydrocarbon contaminants in the soil and the soil gas at every point. Therefore, no diffusional resistances to removal are included and equilibrium dictates the magnitude of hydrocarbon removal rate by the convective flow of soil gas. Using these assumptions, the entire contaminant mass can be considered in contact with the entire gas flow in one equilibrium stage.

A material balance on one component in this stage results in

$$dN_i/dt = -q\ P_i/(RT), \qquad \text{(B-1)}$$

where N_i is the moles of component i in the stage in liquid form, t is time, q is the volumetric gas flow rate, P_i is the partial pressure of component i, R is the ideal gas constant, and T is the absolute temperature.

From Raoult's Law, with its implicit assumption of an ideal solution in the liquid phase and an ideal gas,

$$P_i = x_i\, P_i^{sat}, \qquad \text{(B-2)}$$

where x_i is the mole fraction of component i in the hydrocarbon phase ($x_i = N_i\ /\ N_T$, where N_T is the total number of moles) and P_i^{sat} is the vapor pressure of component i.

Combination of the preceding two equations results in

$$dN_i/dt = -q\ x_i\ P_i^{sat}/(RT). \qquad \text{(B-3)}$$

This equation is solved using the simple BASIC program listed below. In this program, P_i^{sat} for each component is calculated using the Antoine equation,

$$\ln (P_i^{sat}) = A - \frac{B}{(T + C)}\ , \qquad \text{(B-4)}$$

where A, B, and C are empirical constants for each compound. Values for these parameters were taken from The Properties of Gases and Liquids by Reid, Prausnitz, and Sherwood (Reference 10). Since a typical analysis of JP-4 reports a breakdown of 86% paraffins and 14% aromatics, the P_i^{sat} for a hydrocarbon cut was estimated by adding 0.86 P_i^{sat} for the normal paraffin of the range to 0.14 P_i^{sat} of a representative aromatic compound. For instance, P_6^{sat} was estimated as 0.86 $P^{sat}_{n\text{-hexane}}$ + 0.14 $P^{sat}_{benzene}$.

The program performs an accounting of the amount of each compound range present as the material equilibrates with air entering and exiting at a given flow rate. This accounting of the volatilization is accomplished by stepping forward in time with a given time step. The amount of air passed through the venting system during each time step is taken to be the flow rate multiplied by the time step size. This volume is assumed to be in equilibrium with the entire volume of hydrocarbons at atmospheric pressure and the given temperature. The amount of each compound range in the hydrocarbon phase is then found by subtracting the amount necessary to reach

equilibrium in the gas phase (equal to the partial pressure of the range times the gas volume) from the amount in the hydrocarbon phase at the start of the time step. At the end of the time step, new hydrocarbon phase mole fractions are calculated, which allows the calculation of updated values for the P_i for the next time step.

B. USE OF THE MODEL

To use the model, you must have information about the quantity and composition of the contaminants. The quantity of the spill is input to the program as total initial grams of hydrocarbons. The composition of the hydrocarbons is input by weight fractions of each range of hydrocarbons, from C5-C6 to C16-C17. Weight fractions input to the program for simulation of JP-4 venting for comparison to the Hill AFB demonstration project results were:

- C5-C6: 0.0284
- C6-C7: 0.0945
- C7-C8: 0.0881
- C8-C9: 0.118
- C9-C10: 0.144
- C10-C11: 0.159
- C11-C12: 0.0867
- C12-C13: 0.0815
- C13-C14: 0.074
- C14-C15: 0.126.

Other inputs to the program include soil temperature in degrees Fahrenheit, the venting gas flow rate in liters per minute at standard conditions, the time step size used, and the number of time steps between printouts. Because of the equilibrium assumptions made in derivation of the model, the program need only be run one for each combination of contaminant composition and temperature. The output on the computer screen will be made in terms of the hours of operation; however, the files created on disk will be scaled. The first output file presents the results as vapor concentration (gram/liter) and the percent of spill remaining as a function of the cumulative gas volume per mass of initial spill (designated as liter/gram in the output file), and the second presents the average number of carbon atoms per molecule in the hydrocarbons in the liquid and the vapor as a function of liter/gram. Therefore, the results at any time of operation for any spill size or flow rate may be found by multiplying the liter/gram value by the spill quantity and dividing by the extraction gas flow rate.

In cases where it is expected that the equilibrium will control removal, such as homogenous soils and contaminant distribution, the concentration values and cumulative volumes will not require adjustment. The use of an efficiency factor will be necessary for cases of diffusional effects, as would be expected in situations of soil heterogeneities, patchy contaminant distribution, or venting from free product layers. In these cases, the cumulative volume values will have to be divided by the efficiency factor, and the concentration values will have to be multiplied by the efficiency factor for more realistic estimates.

```
10  REM PROGRAM FOR CALCULATION OF CONCENTRATION FROM SOIL
    VENTING OF FUEL HYDROCARBONS
20  REM
30  REM
40  REM USE FUNCTION KEY 1 TO BREAK PROGRAM AND CLOSE FILES
50  ON KEY (1) GOSUB 1420
60  KEY (1) ON:REM NEED /V SWITCH IF COMPILING
70  REM
80  REM OPEN FILES - FILE 1 FOR CONCENTRATION & PERCENT REMAINING
90  REM FILE 2 FOR AVERAGE CARBON NUMBER IN VAPOR & RESIDUAL
100 OPEN "OUTPUT" FOR APPEND AS #1:OPEN "OUT2" FOR APPEND AS #2
110 WRITE #1, "LIT/G", "CONC-G/L", "% REMAIN"
120 WRITE #2, "LIT/G", "WT. AVG C NO. LIQUID", "WT. AVG NO. VAPOR"
130 REM
140 REM C(5) THROUGH C(16) ARE MOLES OF EACH HYDROCARBON RANGE
150 REM MW(5) THROUGH MW(16) ARE MOLECULAR WEIGHTS
160 REM WF(5) THROUGH WF(16) ARE WEIGHT FRACTIONS
170 REM X(5) THROUGH X(16) ARE MOLE FRACTIONS-LIQUID
180 REM Y(5) THROUGH Y(16) ARE MOLE FRACTIONS-VAPOR
190 DIM C(16): DIM MW(16): DIM WF(16): DIM X(16): DIM W(16): DIM Y(16)
200 DIM P(16): DIM R(16): DIM WV(16): DIM PSAT(16)
210 REM SET MOLECULAR WEIGHTS
220 MW(5)=72
230 FOR I=6 TO 16
240 MW(I)=MW(I-1)+14
250 NEXT I
260 REM
270 REM INPUT OF VALUES
280 REM
290 INPUT "ENTER TOTAL WEIGHT OF FUEL,g"; TOT
300 INPUT "ENTER GAS RATES, L/HR"; V
310 INPUT "ENTER FINAL TIME, HRS"; FT
320 INPUT "ENTER TIME STEP SIZE IN HOURS"; DT
330 INPUT "ENTER TEMPERATURE, DEGREES F"; TEMP
340 REM
350 GOSUB 1450: REM CALCULATE VAPOR PRESSURES AT TEMPERATURE
360 REM
370 IDT=DT
380 SUMW=0
390 INPUT "ENTER PRINT FREQUENCY"; PF: INPUT "ENTER TABLE FREQ"; TF
400 IPF=PF
410 FOR I=5 TO 16
420 PRINT "ENTER WEIGHT FRACTION OF C"; I:INPUT WF(I)
430 SUMW=SUMW+WF(I)
440 NEXT I
450 REM
460 PRINT "GAS RATE -";V;"L/HR =";V*.0005887;"CFM": PRINT "INITIAL WT -";TOT:
    PRINT
```

```
470  IF SUMW<.995 THEN PRINT "WEIGHT FRACTIONS DO NOT SUM TO 1!"; SUMW
480  IF SUMW>1.005 THEN PRINT "WEIGHT FRACTIONS DO NOT SUM TO 1!"; SUMW
490  SUM = 0
500  REM INITIALIZE MOLES, WEIGHT FRACTIONS, MOLE FRACTIONS
510  FOR I=5 TO 16
520  C(I)=TOT*WF(I)/MW(I)
530  SUM = SUM + C(I)
540  NEXT I
550  FOR I=5 TO 16
560  X(I)=C(I)/SUM
570  W(I)=C(I)*MW(I)
580  NEXT I
590  REM
600  NS=FT/DT
610  TIME=0
620  REM **********START LOOP**********
630  FOR J=1 TO NS+1
640  LPG=TIME*V/TOT:REM LITERS OF AIR PER GRAMS OF INITIAL
     HYDROCARBONS
650  REM
660  REM ADJUST PRINT RATE AND TIME STEP - SLOW CHANGES LATER IN
     OPERATION
670  IF J>10 THEN PF=IPF*10
680  IF J>100 THEN PF=IPF*100
690  IF J>1000 THEN DT=IDT*10
740  REM
750  REM UPDATE VAPOR PRESSURES
760  FOR I=5 TO 16
770  P(I)=X(I)*PSAT(I)
780  NEXT I
790  PTOT=0
800  SY=0:SW=0:SV=0
810  REM FIND NEW VAPOR COMPOSITION AND CONCENTRATION
820  FOR I=5 TO 16
830  IF W(I)<9.999999e-21 THEN W(I)=0
840  PTOT=PTOT+P(I)
850  Y(I)=P(I)/760
860  SY-SY+Y(I)
870  SW=SW+W(I)
880  WV(I)=Y(I)*MW(I)/22.4
890  SV=SV+WV(I)
900  NEXT I
910  REM CALCULATE AVERAGE CARBON NUMBER IN BOTH PHASES
920  AVCL=0:AVCV=0
930  FOR I=5 TO 16
940  AVCV=AVC+I*WV(I)/SV:AVCL=AVCL+I*W(I)/SW
950  NEXT I
960  REM
```

```
970  REM PRINT ON SCREEN AND IN FILES
980  REM
990  IF (J-1)<>INT((J-1)/TF)*TF THEN GOTO 1090
1000 PRINT:PRINT"TIME =";TIME;"HOURS":PRINT
1010 PRINT TAB(36);"WEIGHT IN";TAB(51);"MOLES";TAB(63);"WEIGHT"
1020 PRINT TAB(9); "X(I)"; TAB(23); "Y(I)"; TAB(36); "VAPOR,g/L"; TAB (49);
1030 PRINT "REMAINING"; TAB(62); "REMAINING"
1040 FOR I=5 TO 16
1050 PRINT "C";I;TAB(6);X(I);TAB(20);Y(I);TAB(34);WV(I);TAB(48);C(I);TAB(62);W(I)
1060 NEXT I
1070 PRINT TAB(23);"----------;TAB(34);"----------";TAB(62);"----------"
1080 PRINT TAB(20);SY;TAB(36);SV;TAB(62);SW:PRINT
1090 IF (J-1)<INT((J-1)/PF)*PF THEN GOTO 1120
1100 PRINT TIME;"HRS";TAB(7);SV;"g/L";TAB(30);SW;"GLEFT";
1110 PRINT TAB(50);SW*100/TOT;"% LEFT"
1120 IF (J-1)=INT((J-1)/PF)*PF THEN WRITE #1, LPG, SV, SW*100/TOT
1130 IF (J-1)=INT((J-1)/PF)*PF THEN WRITE #2, LPG, AVCL, AVCV
1140 REM
1150 REM CALCULATE REMOVAL RATE
1160 REM
1170 FOR I=5 TO 16
1180 REM MOLE REMOVAL RATE= MOLE FRAC*VENT RATE/22.4 L/MOLE
1190 R(I)=Y(I)*V/22.4
1200 NEXT I
1210 SUM=0
1220 REM
1230 REM CALCULATE AMOUNT REMAINING
1240 REM FROM AMOUNT AT START OF TIME STEP - VAPOR CONCENTRATION X
     FLOW RATE
1250 REM
1260 FOR I=5 TO 16
1270 C(I)=C(I)-R(I)*DT
1280 IF C(I)<1E-30 THEN C(I)=0
1290 SUM=SUM+C(I)
1300 W(I)=C(I)*MW(I)
1310 NEXT I
1320 REM
1330 REM UPDATE LIQUID MOLE FRACTIONS - NEEDED FOR UPDATED VAPOR
     PRESSURES
1340 REM
1350 FOR I=5 TO 16
1360 X(I)=C(I)/SUM
1370 NEXT I
1380 REM STEP FORWARD IN TIME
1390 TIME=TIME+DT
1400 NEXT J
1410 REM ************************************END LOOP******************
1420 CLOSE
```

```
1430 STOP
1440 END
1450 REM SUBROUTINE FOR ESTIMATION OF VAPOR PRESSURES
1460 REM ANTOINE EQUATION USED FOR PURE COMPONENTS
1470 REM ESTIMATED VAPOR PRESSURE FOR WEIGHT FRACTION IN JP-4
1480 REM CALCULATED AS 0.86*STRAIGHT CHAIN ALIPHATIC +0.14*
1490 REM PSAT OF AROMATIC HYDROCARBON.
1500 REM ANTOINE EQUATION - LN(PSAT) = ANTA -ANTB/(T+ANTC)
1510 TEMP=(TEMP-32)/1.8+273.15
1520 CPENT=EXP(15.8574-2588.48/(TEMP-41.79))
1530 PENT=EXP(15.8333-2477.07/(TEMP-39.94))
1540 HEX=EXP(15.8366-2697.55/(TEMP-48.78))
1550 BENZ=EXP(15.9008-2788.51/(TEMP-52.36))
1560 HEPT=EXP(15.8737-2911.32/(TEMP-56.51))
1570 TOL=EXP(16.0137-3096.52/(TEMP-53.67))
1580 OCT=EXP(15.9426-3120.29/(TEMP-63.63))
1590 MXYL=EXP(16.139-3366.99/(TEMP-58.04))
1600 NON=EXP(15.9671-3291.45/(TEMP-71.33))
1610 CUME=EXP(15.9722-3363.6/(TEMP-63.37))
1620 DEC=EXP(16.0144-3456.8)/(TEMP-78.67))
1630 NAPH=EXP(16.1426-3992.01/(TEMP-71.29))
1640 UND=EXP(16.0541-3614.07/(TEMP-85.45))
1650 MNAP=EXP(16.2008-4206.7/(TEMP-78.15))
1660 DOD=EXP (16.1134-3774.56/(TEMP-91.31))
1670 TRI=EXP(16.1355-3892.91/(TEMP-98.93))
1680 TETR=EXP(16.148-4008.52/(TEMP-105.4))
1690 ANTH=EXP(17.6701-6492.44/(TEMP-26.13))
1700 PDEC=EXP(16.1724-4121.51/(TEMP-111.8))
1710 HDEC=EXP(16.1841-4214.91/(TEMP-118.7))
1720 PSAT(5)=.86*PENT+.14*CPENT
1730 PSAT(6)=.86*HEX+14*BENZ
1740 PSAT(7)=.86*HEPT+.14*TOL
1750 PSAT(8)=.86*OCT+.14*MXYL
1760 PSAT(9)=.86*NON+.14*CUME
1770 PSAT(10)=.86*DEC+.14*NAPH
1780 PSAT(11)=.86*UND+14*MNAP
1790 PSAT(12)=DOD*PSAT(11)/UND
1800 PSAT(14)=.86*TETR+.14*ANTH
1810 PSAT(13)=TRI*PSAT(14)/TETR
1820 PSAT(15)=PDEC*PSAT(14)/TETR
1830 PSAT*16)=HDEC*PSAT(14)/TETR
1840 RETURN
1850 END
```

APPENDIX C

DERIVATION OF CONCEPTUAL DESIGN EQUATIONS

A. VERTICAL VENTS

To determine the number of vents necessary and the suction at each vent, a model of air flow through soil must be considered. For conceptual design purposes, it is assumed that all flow is horizontal and is distributed with angular symmetry around a single vent. In practice, this is not likely to be the case, since air flow from the surface will introduce a vertical component, soil inhomogeneities will cause uneven flow distribution, and multiple vents in operation will have overlapping effects. Therefore, for more detailed design, a two- or three-dimensional numerical model would be more realistic.

This one-dimensional radial flow case is illustrated in Figure 9 in the main body of this document. The air extraction rate from the vent, assuming compressible ideal gas flow, may be expressed as

$$q = \frac{\pi k h (P_{atm}^2 - P_v^2)}{\mu P_v \ln\left[\frac{r_{atm}}{r_v}\right]} \quad , \tag{C-1}$$

where q is the volumetric extraction flow rate at the conditions of the vent ($q=Q/N$, where N is the number of operating vents and Q is the total extraction flow rate), k is the air permeability of the soil, P_{atm} is the absolute atmospheric pressure, P_v is the pressure in the extraction vent, h is the length of the slotted section of the vent, μ is the viscosity of the air, r_v is the radius of the vent, and r_{atm} is the minimum radial distance from the center of the vent where the pressure is essentially atmospheric.

Within a given radius of influence r_i, this flow treats a soil volume of $\pi r_i^2 h$, which contains a contaminant mass of $\pi r_i^2 h C_{av}$, where C_{av} is the concentration of the contaminant expressed in terms of mass per volume of soil (if concentration values are available in mg contaminant/kg soil, multiply by the density of the soil to get C_{av}). For this contaminant mass to be treated, it must, on average, reach the removal factor chosen,

$$RF = \frac{q(PC)t}{\pi r_i^2 h C_{av}} \quad , \tag{C-2}$$

where *RF* is the removal factor (liters of air per gram of contaminant, such as from Figure 7 of this document), *PC* is a pressure correction to adjust the flow rate at the vent conditions to the conditions for which *RF* was derived, and *t* is the time for cleanup found in Equation (19) of this document.

The pressure correction for ideal gas conditions is

$$PC = \left(\frac{P_v}{P_{atm}}\right)\left(\frac{P_{av}}{P_{atm}}\right) \quad . \tag{C-3}$$

The term P_v/P_{atm} adjusts the flow rate at the vent from P_v to P_{atm}, for which *RF* was derived. The second term, P_{av}/P_{atm}, where P_{av} is the volume averaged pressure within the radius of influence, is added to account for the change in equilibrium removal rates with pressure, which varies as a function of radius. As can be deduced from the results shown in Reference 2, P_{av} will likely not differ greatly from P_{atm} (for most reasonable cases $0.9 < P_{av}/P_{atm} < 1.0$); therefore the conservative estimate of $P_{av}/P_{atm} = 1$ is made.

Combination of Equations (C-1), (C-2), and (C-3) results in

$$RF = \frac{kt(P_{atm}^2 - P_v^2)}{r_i^2 C_{av} \mu P_{atm} \ln\left[\frac{r_{atm}}{r_v}\right]} \tag{C-4}$$

Therefore, given the time desired for cleanup, the air permeability of the soil, the average contaminant concentration in the soil, and desired values for the radius of influence and removal factor, the vacuum necessary at the extraction vent may be estimated.

The radius of influence is set by defining the number of vents,

$$r_i = \sqrt{\frac{A}{\pi N}} \tag{C-5}$$

where *A* is the contamination area.

In order to solve for the suction pressure required at the vent to extract the flow rate q, an assumption must be made as to the relationship between r_i and r_{atm}. It is obvious that r_{atm} must be

greater than or equal to r_i, otherwise the radius of treated soil would be larger than the radius within which substantial flow occurs. For design purposes, a ratio of $r_{atm}/r_i=2$ will be selected. This appears to be a realistic estimate and will likely give reasonable results, since Equation (C-4) is much more sensitive to variations of r_i than to r_i/r_{atm}. For more perfect radial flow, or for more conservative estimates of P_v, the ratio may be increased. Substitution of Equation (C-5) and the assumed relationship of r_{atm} and r_i into Equation (C-4) results in,

$$RF = \frac{\pi k t N (P_{atm}^2 - P_v^2)}{A \mu C_{av} P_{atm} \ln\left[\frac{2}{r_v}\left(\frac{A}{\pi N}\right)^{1/2}\right]} \tag{C-6}$$

This equation may be solved to find P_v by using the quadratic formula. The positive root is used, since the negative root results in negative absolute pressures, a physical impossibility. The solution for P_v is,

$$P_v = \left(P_{atm}^2 - \frac{C_{av} \mu P_{atm} RFA \; ln\left[\frac{2}{r_v}\left(\frac{A}{N\pi}\right)^{1/2}\right]}{\pi N k t}\right)^{1/2} \tag{C-7}$$

Defining DP as the vacuum at the extraction vent,

$$DP = P_{atm} - P_v = P_{atm} - \left(P_{atm}^2 - \frac{C_{av} \mu P_{atm} RFA \; ln\left[\frac{2}{r_v}\left(\frac{A}{N\pi}\right)^{1/2}\right]}{\pi N k t}\right)^{1/2} . \tag{C-8}$$

B. HORIZONTAL VENTS

1. Vacuum Requirement

The assumptions made in derivation of the design equation for horizontal vents are similar to the vertical vent case. The model of air flow for this case is illustrated in Figure 11 of this document. A lateral vent of slotted section length L is placed at a depth D in the soil. Air flow is distributed with radial symmetry above the vent. It is assumed that no flow is induced below the vent. Adjustment of Equation (C-1) for this semicircular case results in

$$q = \frac{\pi k L(P_{atm}^2 - P_v^2)}{2\mu P_v \ln\left[\frac{D}{r_v}\right]} \tag{C-9}$$

where q is the volumetric extraction flow rate at the conditions of the vent ($q=Q/N$, where N is the number of operating vents), k is the air permeability of the soil, P_{atm} is the absolute atmospheric pressure, P_v is the pressure in the extraction vent, L is the length of the slotted section of the vent, μ is the viscosity of the air, D is the depth of the extraction vent, and r_v is the radius of the vent.

In this case, the effective radius of influence of the vent is D. The soil volume treated by a single vent is thus approximated by $\pi D^2L/2$, which contains a contaminant mass of $\pi D^2LC_{av}/2$, where C_{av} is the average contaminant concentration in the soil. For this contaminant mass to be treated, it must, on average, reach the removal factor chosen,

$$RF = \frac{2qPCt}{\pi D^2 L C_{av}} \tag{C-10}$$

where RF is the removal factor (liters of air per gram of contaminant), PC is the pressure correction to adjust the flow rate at the vent conditions to the conditions for which RF was derived, and t is the time for cleanup. As in the vertical vent case, PC is approximated by P_v/P_{atm}.

Combination of the above equations results in,

$$RF = \frac{kt(P_{atm}^2 - P_v^2)}{D^2 C_{av} \mu P_{atm}\ ln\left[\frac{D}{r_v}\right]} \tag{C-11}$$

The quadratic formula may be used to solve for the vacuum at the vent,

$$DP = P_{atm}\ P_v = P_{atm} - \left(\frac{P_{atm}^2 - C_{av} D^2 \mu P_{atm} RF\ ln\left[\frac{D}{rv}\right]}{kt} \right)^{1/2} \tag{C-12}$$

Thus, the vacuum required at a horizontal vent to induce adequate flow for contaminant removal in a given period may be estimated as a function of removal factor, depth, air permeability, and soil concentration.

2. Vent Spacing

It should be noted that there is no explicit dependence on N, the number of operating vents, in the above equation. For this equation to be used as an approximation of performance, the entire contaminated soil volume, assumed of depth D, length L, and width W, must be treated. For this to be true, the product of the number of vents with the effective volume of a single vent must equal the contaminated soil volume,

$$N\left(\frac{\pi D^2 L}{2}\right) = DWL \quad . \tag{C-13}$$

By simplification it is found that the necessary maximum distance between vents is,

$$\text{vent spacing} = \frac{W}{N} = \frac{\pi D}{2} \quad . \tag{C-14}$$

From this simplified approach, it is seen that horizontal vents should be placed no farther apart than about 1.5 times their depth. Depending on the cost of installation, it is likely that it would be preferable to place vents closer than the maximum spacing to allow flexibility of operation.

APPENDIX D

TWO-DIMENSIONAL ANALYTICAL MODEL FOR ISSV

The program IMAGE.FOR was written in Fortran 77 and tested on an IBM-AT compatible using the Microsoft 5.1 compiler. It calculates the pressure and velocity due to a point source using the Method of Images solution discussed in the text of this report. Use of the program is documented in the program comments and an example interactive session is given below. IMAGE writes two ASCII files. The first is a SURFER (GOLDEN GRAPHICS, Golden, CO) data file used to produce a contour of the pressure. The units are Pascals and the values are changes from no pumping (zero pressure). The second file is a SURFER data file with four columns: (1) R-coordinate of grid point in meters, (2) Z-coordinate of grid point in meters, (3) Darcy velocity in meters/second, and (4) direction in degrees. This can be used as a SURFER post file, superimposing the velocities on the pressure contours. This is illustrated in Figure D-1 for the data set generated in the example run. The arrow symbol is posted with a size linearly proportional to the velocity and an angle taken from column 4 in the data file. Note that the contours near the source have been omitted to make it easier to see the arrows and that the arrows near the source have been omitted. If plotted, the arrows near the source would have been several inches long.

```
C:\GWATER\ANALYTIC>image
SEPARTE ENTRIES ON A LINE WITH SPACES OR COMMAS
 ENTER RLO, RHI, ZLO, ZHI
0,30,-15,0
 ENTER THE NUMBER OF R AND Z GRIDLINES
31,31
 ENTER DEPTH TO SOURCE AND FLOW RATE
-3.1,-.1
 ENTER INTRINSIC AND RELATIVE PERMEABITIES
3.0e-11,1.0
( 1)NO FLOW OR (2)CONSTANT PRESSURE SURFACE?
1
 ENTER NAME OF GRID FILE (MUST END IN .GRD)
test.grd
 ENTER NAME OF POST FILE (MUST END IN .DAT)
test.dat
 THE DATA YOU HAVE ENTERED IS:
 ----------------------------
 RLO =    0.000000000000000E+000 RHI =       30.000000000000000
 ZLO =       -15.000000000000000 ZHI =    0.000000000000000E+000
 NR  =             31 NZ=              31
 DEPTH TO SOURCE =          -3.100000000000000
 SOUCE/SINK STRENGTH =   -1.000000000000000E-001
 THE INTRINSIC AND RELATIVE PERMEABILITES ARE:
  3.000000000000000E-011          1.000000000000000
 THE SURFACE BOUNDARY IS:
NO FLOW
 THE OUTPUT GRID FILE IS: test.grd
 THE OUTPUT POST FILE IS: test.dat

 IS THIS DATA CORRECT?
yes
Stop - Program terminated.

C:\GWATER\ANALYTIC>
```

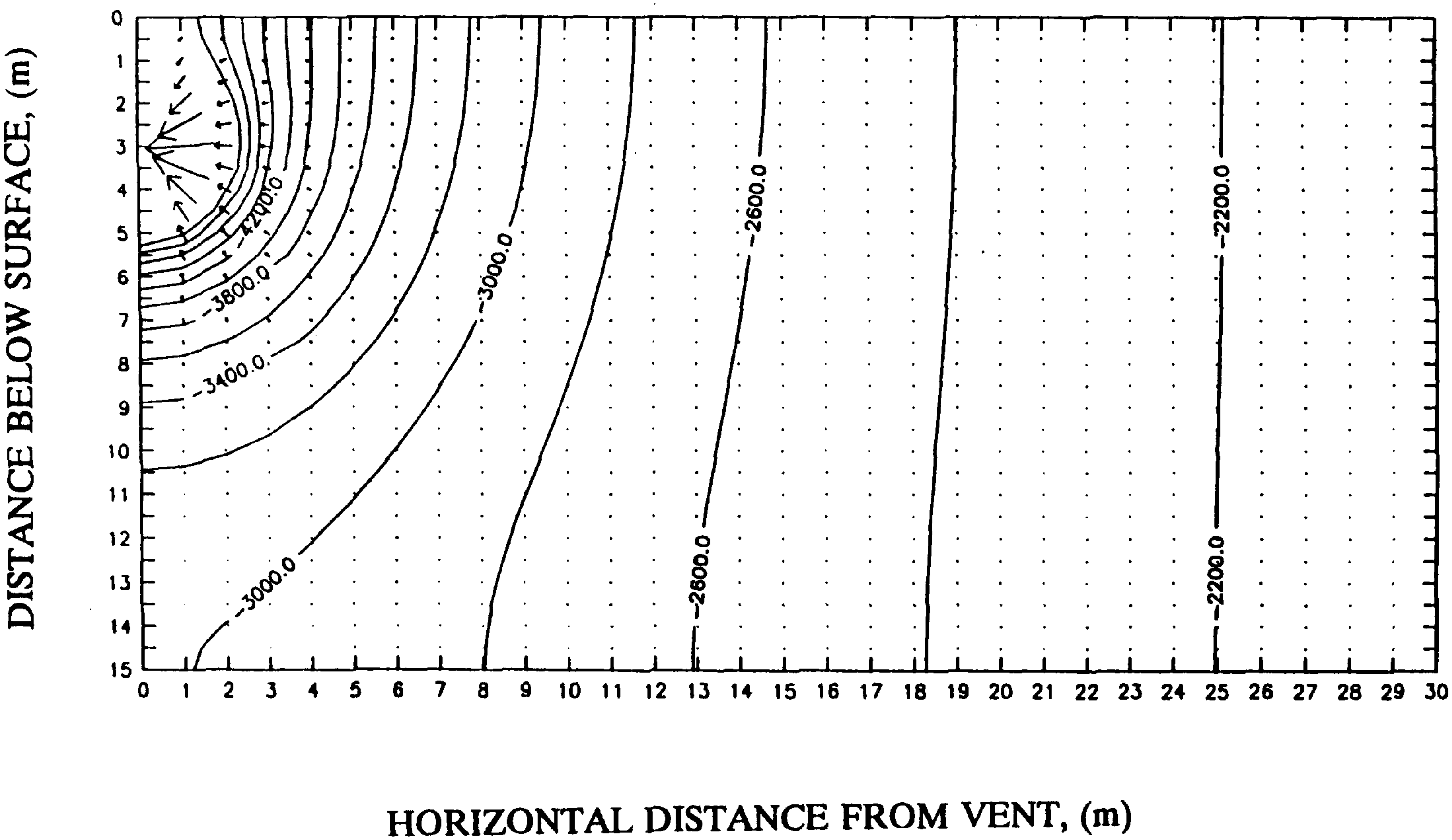

Figure D-1. Pressure and Velocity Profiles for Example IMAGE.FOR Run. Contours are Pressure in Pascals, Relative to Atmospheric Pressure.

```
*****************************************************************************
                             PROGRAM IMAGE
*****************************************************************************
*                     This program uses the Method of Images solution       *
*                     described in the Guidance Document to compute the     *
*                     pressures and flow rates resulting from a point       *
*                     source or sink at r=0, and at a user specified        *
*                     depth.  The output is in the form of a SURFER         *
*                     (Golden Graphics) gridfile.  The program could be     *
*                     easily changed to use a different output format.      *
*                                                                           *
*     Input Variables:                                                      *
*     D   :Depth to source/sink (meters)                                    *
*     T   :Layer thickness (meters)                                         *
*     Q   :Pumping rate (m3/s), + = source, - = sink.                       *
*     KI  :Intrinsic Permeability (m2)                                      *
*     KR  :Relative Permeability (0-1, dimensionless)                       *
*     RLO :Minimum radius (meters), if zero the program will bomb if        *
*          if the source/sink is also on a gridline because of the          *
*          singularity.                                                     *
*     RHI :Maximum radius of grid (meters)                                  *
*     ZLO :Elevation of bottom of the layer (maximum depth, meters)         *
*     ZHI :Elevation of the top of the layer (minimum depth, meters)        *
*     NR  :Desired number of radial grid lines                              *
*     NZ  :Desired number of vertical grid lines                            *
*     (note -- more lines, smoother contours, but more computations)        *
*     COVER:Upper boundary no flow (+1), or constant pressure (-1)          *
*                                                                           *
*     Output Variables in Grid File:                                        *
*     'DSAA'              :Code required by SURFER                          *
*     NR, NZ              :as above                                         *
*     RLO,RHI             :as above                                         *
*     ZLO,ZHI             :as above                                         *
*     PLO,PHI             :Minimum and maximum pressures (Pascals)          *
*     grid row 1                                                            *
*     grid row 2                                                            *
*     grid row 3....      :Pressure values organized in row order, each     *
*                          row has a constant z coordinate.  First row is   *
*                          ZLO, etc.  Each row runs from XLO to XHI.        *
*                                                                           *
*     The second file written by the program contain the flow velocity      *
*     and direction at each grid point.  This file could be used as a       *
*     post file to put velocity arrows on the pressure plot, or using       *
*     the SURFER grid program it could be contoured.                        *
*                                                                           *
*     Output Variables in Post File are lines containing:                   *
*     R, Z, V, THETA                                                        *
*     for each grid point, where                                            *
*     R = radius, Z = elevation, V = velocity (m/s), and theta = angle (deg) *
*                                                                           *
*     Jonathan E. Nyquist, March 1990                                       *
*****************************************************************************
```

```
      IMPLICIT LOGICAL(A-Z)
      INTEGER NR,NZ,I,J,IN,OUT1,OUT2,COVER
      CHARACTER*12 GRIDFILE, POSTFILE
      REAL P(100), V, THETA
      REAL MU,PI,D,Q,KI,KR,RLO,RHI,ZLO,ZHI,T,DR,DZ,R,Z,PLO,PHI

*     ....MU is the dynamic viscosity of air (kg/m/s)....
      PARAMETER( MU = 1.9E-5  )
      PARAMETER( PI = 3.14159 )
      PARAMETER( IN = 5, OUT1 = 6, OUT2 = 7 )

*     ....get and echo the input parameters....
      CALL INPUT(D,Q,KI,KR,RLO,RHI,ZLO,ZHI,NR,NZ,IN,OUT1,GRIDFILE,
     1 POSTFILE,COVER)

*     ....write out the gridfile....
      OPEN(OUT2,FILE=GRIDFILE)
      WRITE(OUT2,'(A4)') 'DSAA'
      WRITE(OUT2,*)  NR, NZ
      WRITE(OUT2,*) RLO, RHI
      WRITE(OUT2,*) ZLO, ZHI

*     ....Dummy values are assigned to phi and plo, SURFER recomputes these...
      PHI =  1.0e15
      PLO = -1.0e15
      WRITE(OUT2,*) PLO, PHI

*     ....Begin Computations....
      DR = (RHI-RLO)/REAL(NR-1)
      DZ = (ZHI-ZLO)/REAL(NZ-1)
      T   = ABS(ZHI-ZLO)
      DO 100, I=1,NZ
         Z = ZLO + (I-1)*DZ
         DO 50, J=1,NR
            R = RLO + (J-1)*DR
            CALL PRESSURE(R,Z,D,T,Q,COVER,MU,PI,KI,KR,P(J))
 50      CONTINUE
         WRITE(OUT2,'(6E13.5)') (P(J), J=1,NR)
100   CONTINUE
      CLOSE(OUT2)

*     ....write out postfile....
      OPEN(OUT2,FILE=POSTFILE)
      DO 200, I=1,NZ
         Z = ZLO + (I-1)*DZ
         DO 150 J=1,NR
            R = RLO + (J-1)*DR
            CALL VELOCITY(R,Z,D,T,Q,COVER,PI,V,THETA)
            WRITE(OUT2,*) R,Z,V,THETA
150      CONTINUE
200   CONTINUE
      STOP
      END
```

```
*-----------------------------------------------------------------------
      SUBROUTINE INPUT(D,Q,KI,KR,RLO,RHI,ZLO,ZHI,NR,NZ,IN,OUT1,
     1                GRIDFILE,POSTFILE,COVER)
    IMPLICIT LOGICAL (A-Z)
      CHARACTER ANS*3, GRIDFILE*12, POSTFILE*12
      INTEGER IN,OUT1,NR,NZ,COVER
      REAL D,Q,KI,KR,RLO,RHI,ZLO,ZHI

*     .... Read in the parameters....
  10  WRITE(OUT1,*) 'SEPARATE ENTRIES ON A LINE WITH SPACES OR COMMAS'
      WRITE(OUT1,*) ' ENTER RLO, RHI, ZLO, ZHI'
      READ(IN,*) RLO, RHI, ZLO, ZHI
      WRITE(OUT1,*) ' ENTER THE NUMBER OF R AND Z GRIDLINES'
      READ(IN,*) NR, NZ
      WRITE(OUT1,*) ' ENTER DEPTH TO SOURCE AND FLOW RATE '
      READ(IN,*) D, Q
      WRITE(OUT1,*) ' ENTER INTRINSIC AND RELATIVE PERMEABILITIES'
      READ(IN,*) KI, KR
      WRITE(OUT1,*) '( 1)NO FLOW OR (2)CONSTANT PRESSURE SURFACE?'
      READ(IN,*) COVER
      IF (COVER .EQ. 2) COVER = -1
      WRITE(OUT1,*) ' ENTER NAME OF GRID FILE (MUST END IN .GRD)'
      READ(IN,'(A)') GRIDFILE
      WRITE(OUT1,*) ' ENTER NAME OF POST FILE (MUST END IN .DAT)'
      READ(IN,'(A)') POSTFILE

*     ....Echo the input....
      WRITE(OUT1,*) ' THE DATA YOU HAVE ENTERED IS:'
      WRITE(OUT1,*) ' -----------------------------'
      WRITE(OUT1,*) ' RLO = ',RLO,' RHI = ',RHI
      WRITE(OUT1,*) ' ZLO = ',ZLO,' ZHI = ',ZHI
      WRITE(OUT1,*) ' NR  = ',NR,' NZ= ',NZ
      WRITE(OUT1,*) ' DEPTH TO SOURCE = ', D
      WRITE(OUT1,*) ' SOUCE/SINK STRENGTH = ', Q
      WRITE(OUT1,*) ' THE INTRINSIC AND RELATIVE PERMEABILITIES ARE:'
      WRITE(OUT1,*)   KI,KR
      WRITE(OUT1,*) ' THE SURFACE BOUNDARY IS:'
      IF(COVER.EQ.1) THEN
         WRITE(OUT1,*) 'NO FLOW'
      ELSEIF(COVER.EQ.-1) THEN
         WRITE(OUT1,*) 'ATMOSPHERIC PRESSURE'
      ELSE
         WRITE(OUT1,*) ' MESSED UP'
      ENDIF
      WRITE(OUT1,*) ' THE OUTPUT GRID FILE IS: ', GRIDFILE
      WRITE(OUT1,*) ' THE OUTPUT POST FILE IS: ', POSTFILE
      WRITE(OUT1,*)
      WRITE(OUT1,*) ' IS THIS DATA CORRECT?'
      READ(IN,'(A)') ANS
      IF(ANS(1:1).EQ.'N' .OR. ANS(1:1).EQ.'n') GOTO 10
      RETURN
      END
```

```
*-------------------------------------------------------------------------------
      SUBROUTINE VELOCITY(R,Z,D,T,Q,COVER,PI,V,THETA)
      IMPLICIT LOGICAL(A-Z)
      REAL R,Z,PI,D,T,Q,V,THETA
      INTEGER COVER

*                 ..Calculates the velocity at (r,z) due to a source/sink
*                 at (0,D).

      INTEGER I
      REAL VROLD,VRNEW,VR1,VR2,VRTOTAL
      REAL VZOLD,VZNEW,VZ1,VZ2,VZTOTAL
      VRTOTAL = 0.0
      VZTOTAL = 0.0
      DO 100, I=-10,10
*        ....Radial Velocity....
         VROLD = VRTOTAL
         VR1 =           (R)/(R**2+(Z-D+2*I*T)**2)**1.5
         VR2 = COVER * (R)/(R**2+(Z+D+2*I*T)**2)**1.5
         VRNEW = COVER**I * (VR1+VR2)
         VRTOTAL = VRTOTAL + VRNEW
*        ....Z Velocity....
         VZOLD = VZTOTAL
         VZ1 =           (Z-D+2*I*T)/(R**2+(Z-D+2*I*T)**2)**1.5
         VZ2 = COVER * (Z+D+2*I*T)/(R**2+(Z+D+2*I*T)**2)**1.5
         VZNEW = COVER**I * (VZ1+VZ2)
         VZTOTAL = VZTOTAL + VZNEW
  100 CONTINUE
      VRTOTAL = Q*VRTOTAL/(4.0*PI)
      VZTOTAL = Q*VZTOTAL/(4.0*PI)
      V = SQRT((VRTOTAL**2+VZTOTAL**2))
      THETA =  360.0*ATAN2(VZTOTAL,VRTOTAL)/(2*PI)
      RETURN
      END
*-------------------------------------------------------------------------------
      SUBROUTINE PRESSURE(R,Z,D,T,Q,COVER,MU,PI,KI,KR,P)
      IMPLICIT LOGICAL(A-Z)
      REAL R,Z,MU,PI,KI,KR,P,D,T,Q
      INTEGER COVER

*                 ..Calculates the pressure at (r,z) due to a source/sink
*                 at (0,D).

      INTEGER I
      REAL POLD,PNEW,P1,P2,PTOTAL
      PTOTAL = 0.0
      DO 100, I=-10,10
         POLD = PTOTAL
         P1 =           (1.0)/SQRT(R**2 + (Z - D + 2*I*T)**2)
         P2 = COVER * (1.0)/SQRT(R**2 + (Z + D + 2*I*T)**2)
         PNEW = COVER**I * (P1+P2)
         PTOTAL = PTOTAL + PNEW
  100 CONTINUE
      P = Q*MU*PTOTAL/(4*PI*KI*KR)
      RETURN
      END
*-------------------------------------------------------------------------------
```

APPENDIX E

ILLUSTRATIVE EXAMPLES OF CALCULATIONS WITH FEMAIR FLOW MODEL FOR POROUS MEDIA

The FEMAIR numerical model for air flow through porous media was used to show how vent placement affects flow behavior under various ground conditions. The results of the calculations are presented in this appendix. By identifying the flow geometries which most closely match those of the site of interest, the pressure and flow distribution diagrams which follow may be used to visualize the flow field induced and the zones of high and low contaminant removal. This provides a basis for adjustment of vent placement to correspond with known information on site features and contaminant distribution.

For each of the several illustrative examples presented, a figure is given which consists of three frames. The first frame of each example shows a schematic of the vent installation (i.e., vent depth, length of screened section of vent, and extent of surface barrier, if present) and the locations of no-flow boundaries and clay layers, if present. The second frame shows isobars, or contours of equal pressure. In the third frame, contours of equal flow velocity are presented.

To understand how to interpret the plots, consider the relatively simple case in Figure E-1 for a single extraction vent in homogeneous sand with no surface barrier and an impermeable zone extending downward from 18 meters. The vent geometry, showing the screened interval of the vent from 3 to 15 meters below land surface, is presented in frame 1. Frames 2 and 3 show calculated pressure and flow data for extraction from the vent. The data are specifically for a vent diameter of 0.1 meter, soil permeability of 2.8×10^{-11} m^2, and an extraction flow rate of 0.0708 m^3/second. However, the shape of the curves will generally apply.

In frame 2 of Figure E-1, isobars, or contours of equal pressure, are shown. The data are presented as vacuum in Pascals (e.g., a value of 100 indicates that the pressure is 100 Pascals less than atmospheric). On such vacuum plots, air flow will be perpendicular, or normal, to the constant vacuum contours and in the direction of increasing vacuum values. For example, on the 100 Pa contour, the flow will be (1) almost vertical close to the well, (2) at about a 45-degree angle at approximately 13 meters from the well, and (3) almost horizontal at 20 meters from the well.

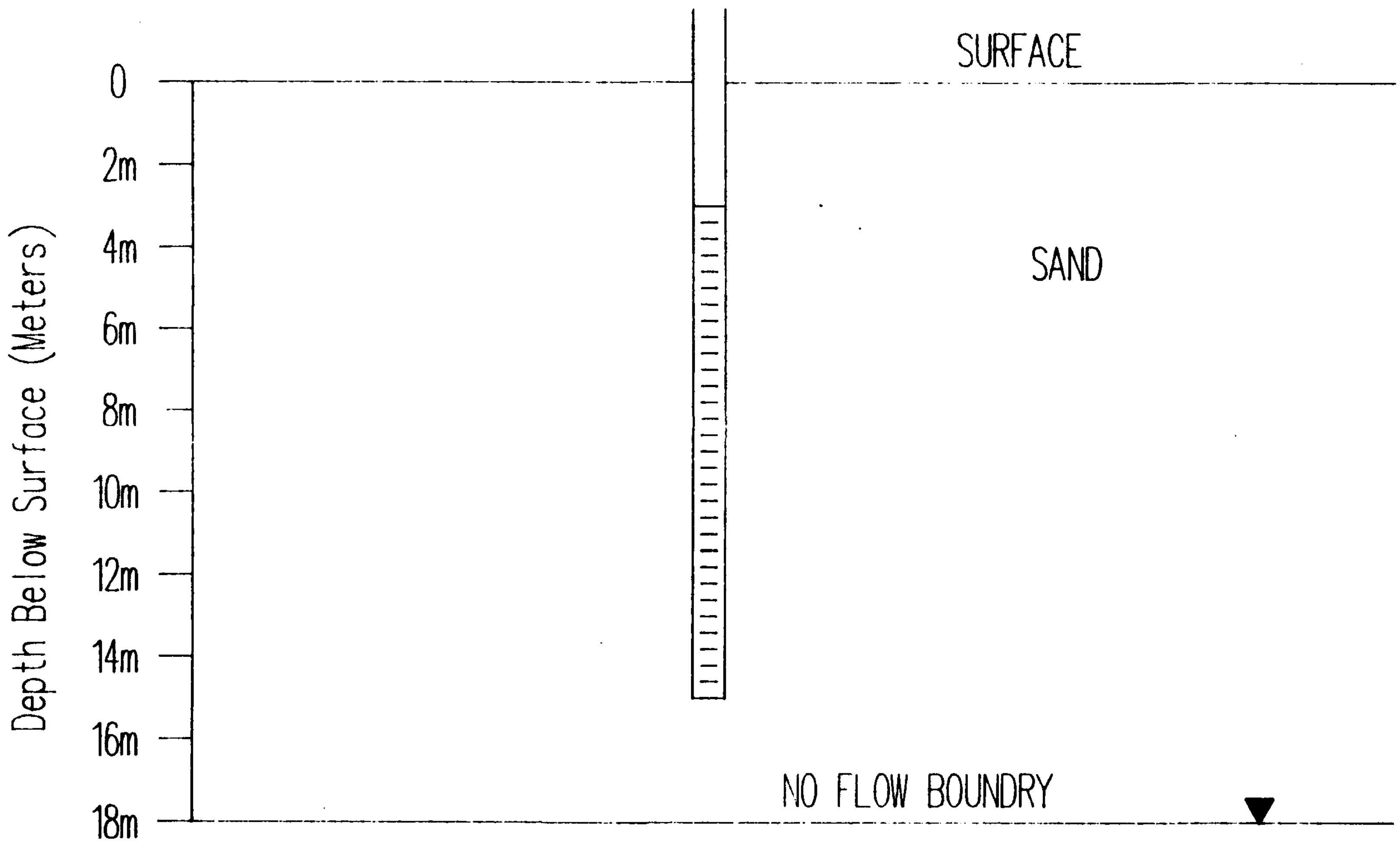

Figure E-1 (Frame 1). FEMAIR Modelling Results - Vent with Screen at 3-15 Meters; No Surface Barrier.

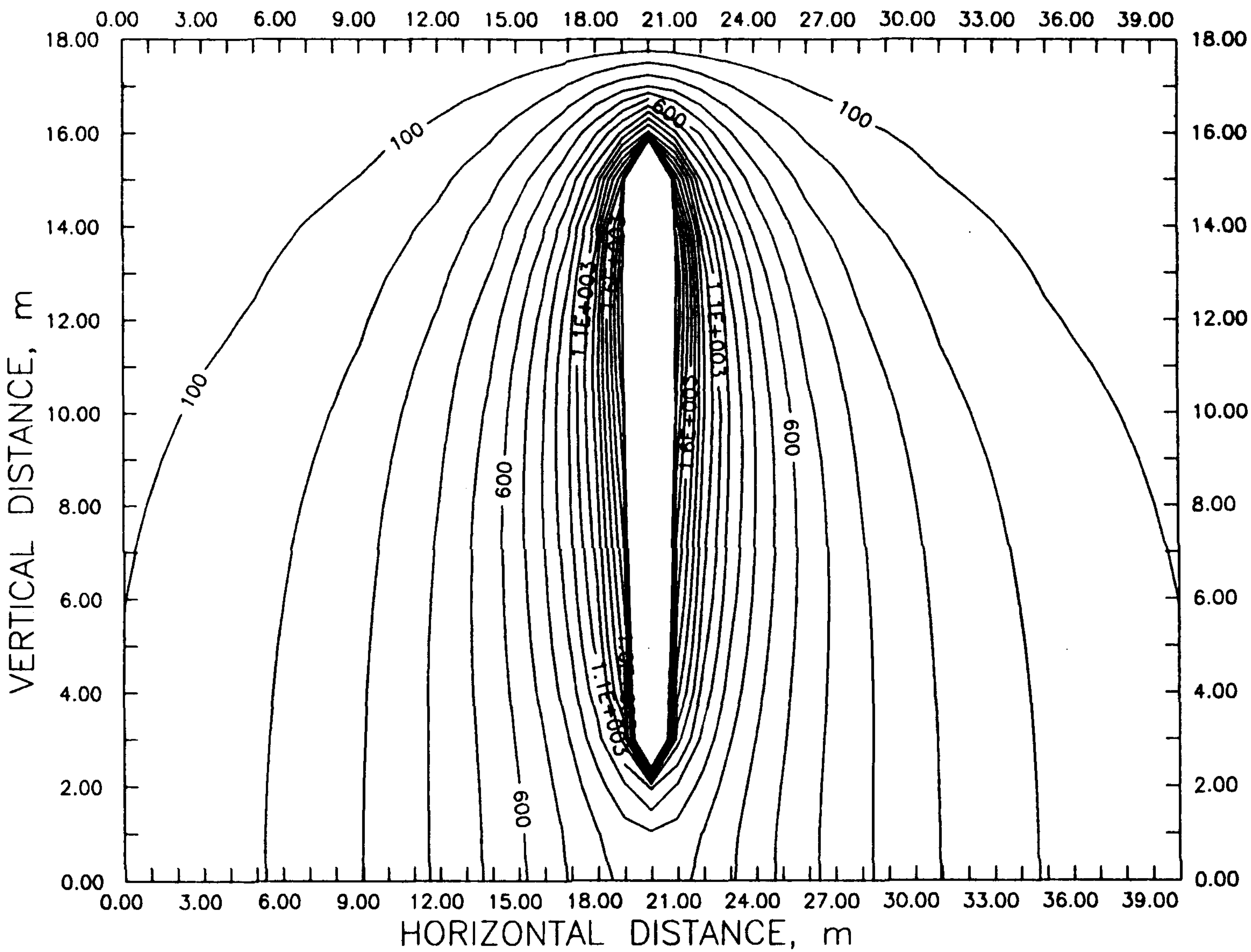

Figure E-1 (Frame 2). FEMAIR Modelling Results - Pressure Contours for Vent with Screen at 3-15 Meters; No Surface Barrier (Continued).

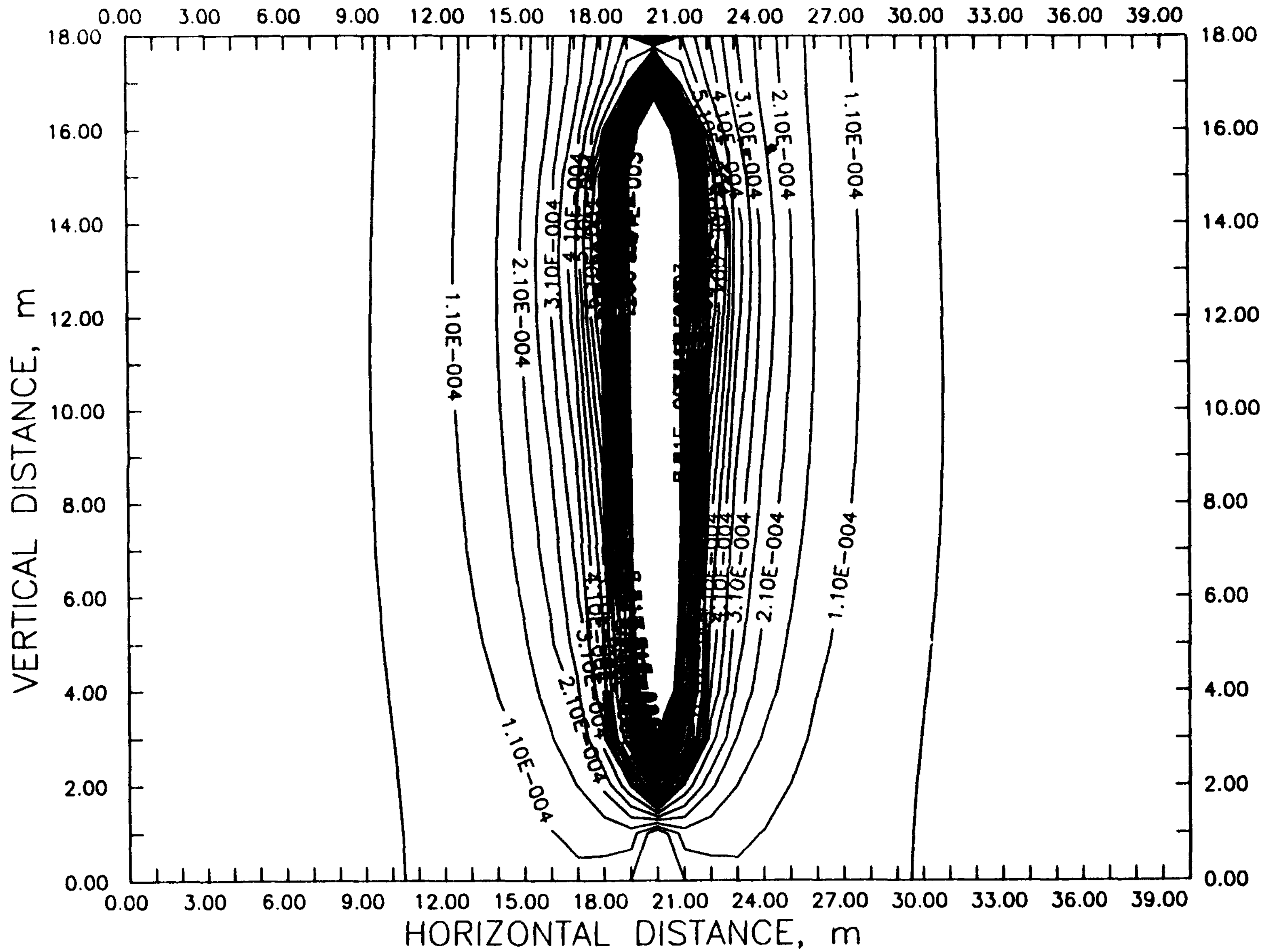

Figure E-1 (Frame 3). **FEMAIR Modelling Results - Flow Contours for Vent with Screen at 3-15 Meters; No Surface Barrier (Concluded).**

Frame 3 of Figure E-1 presents contours of the flow intensity, or the magnitude of the velocity vector, at each point in the soil. The data are presented as meters/second. The flow intensity is proportional to the product of the vacuum gradient (the difference in vacuum between contours divided by the distance between the contours) and the permeability. The flow intensity is a measure of how much air flow, regardless of direction, is passing through a point in the soil per unit of time. Since contaminant removal rate is based largely upon flow rate, contours of flow intensity allow one to visualize which zones are being better treated with different well placements, as can be seen from an examination of frames 2 and 3. The flow intensity on the 100 Pa contour decreases with horizontal distance from the well.

When "fresh," or uncontaminated, air enters a contaminated zone at a certain point, the path it takes to the vent is always perpendicular to the vacuum contours, as pointed out above. The volume flow rate of air passing through a differential area at the entrance to the contaminated zone is equal to the velocity times the area at that point. The amount of contaminated soil contacted by the "fresh" air is related to the length of the path between the point of entrance of the air to the contaminated zone and the point where the air enters the vent. According to the equilibrium model discussed in Section IV, the greater the ratio of air flow rate to the amount of contamination, the faster the cleanup of the soil will occur. Thus, if the area of Figure E-1 is uniformly contaminated and no contamination exists outside the boundaries, it would appear that cleanup would occur most quickly in the region around the top of the vent since the flow at the surface is relatively high and the path to the vent is short. Longer and longer cleanup times would be required for areas that are deeper below the surface and further horizontally from the vent. To predict how cleanup in the soil would actually proceed with time, modification of the air flow model to include mass transfer would be necessary.

Additional cases are described below. In all cases, the vent diameter is 0.1 meter. In the cases in which a surface barrier is present, the barrier is assumed to extend either 15 meters or 100 meters from the well. The soil either consists of sand, with an air permeability of 2.8×10^{-11} m^2 (which approximates the conditions at Hill AFB), or of separate layers of sand and clay, the latter having a permeability of 2.8×10^{-14} m^2. The total flow rate was set in each case so that the maximum vacuum value was in the range of 7500-15000 Pa (30-60 inches of water).

In the case shown in Figure E-2, the screen on the extraction well extends to the same depth as in Figure E-1, but the screen is only one half as long. The vacuum and flow intensity contours in frames 2 and 3 are similar to those of Figure E-1, except that they are displaced downward, providing better treatment in the lower soil zones.

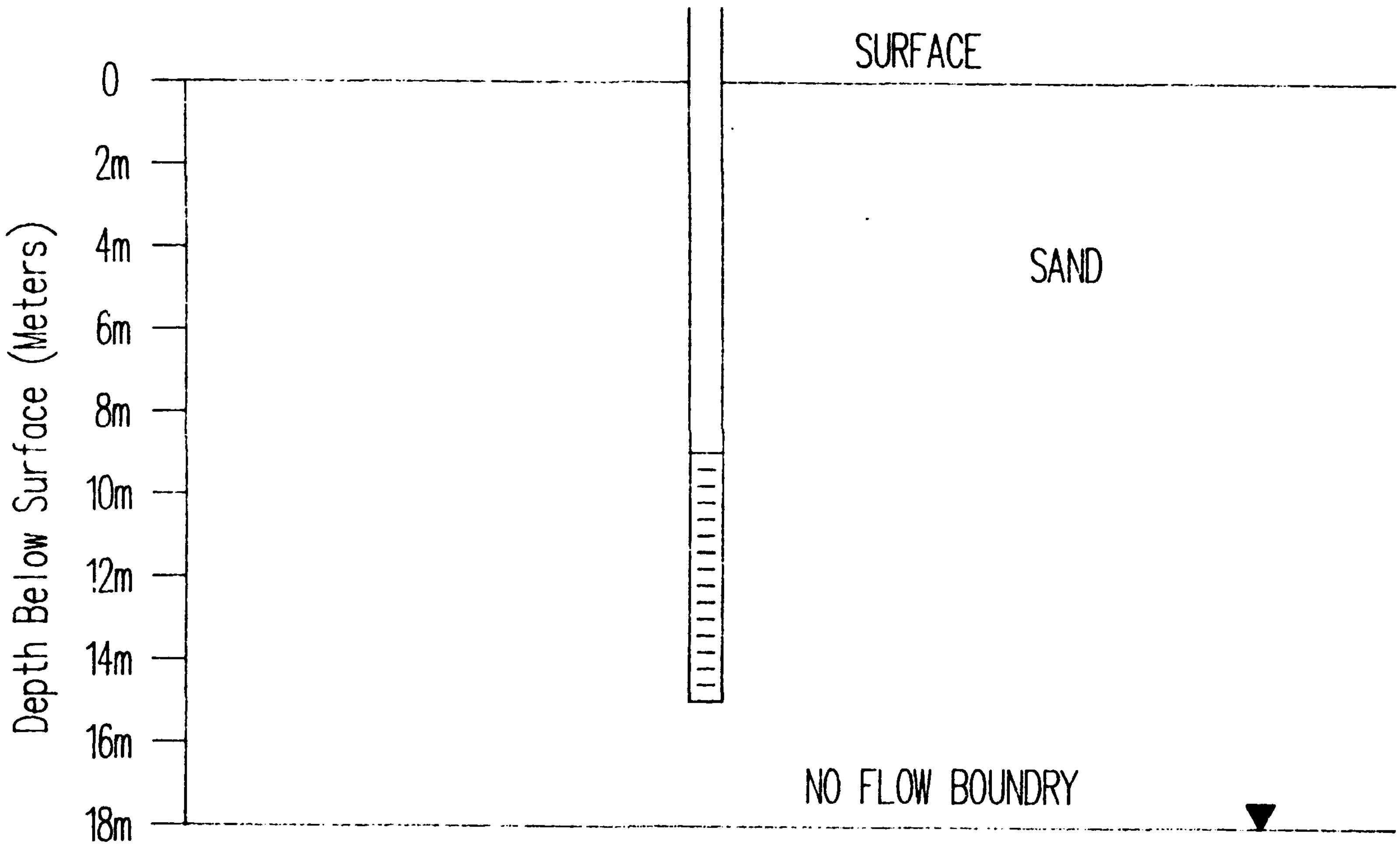

Figure E-2 (Frame 1). FEMAIR Modelling Results - Vent with Screen at 9-15 Meters; No Surface Barrier.

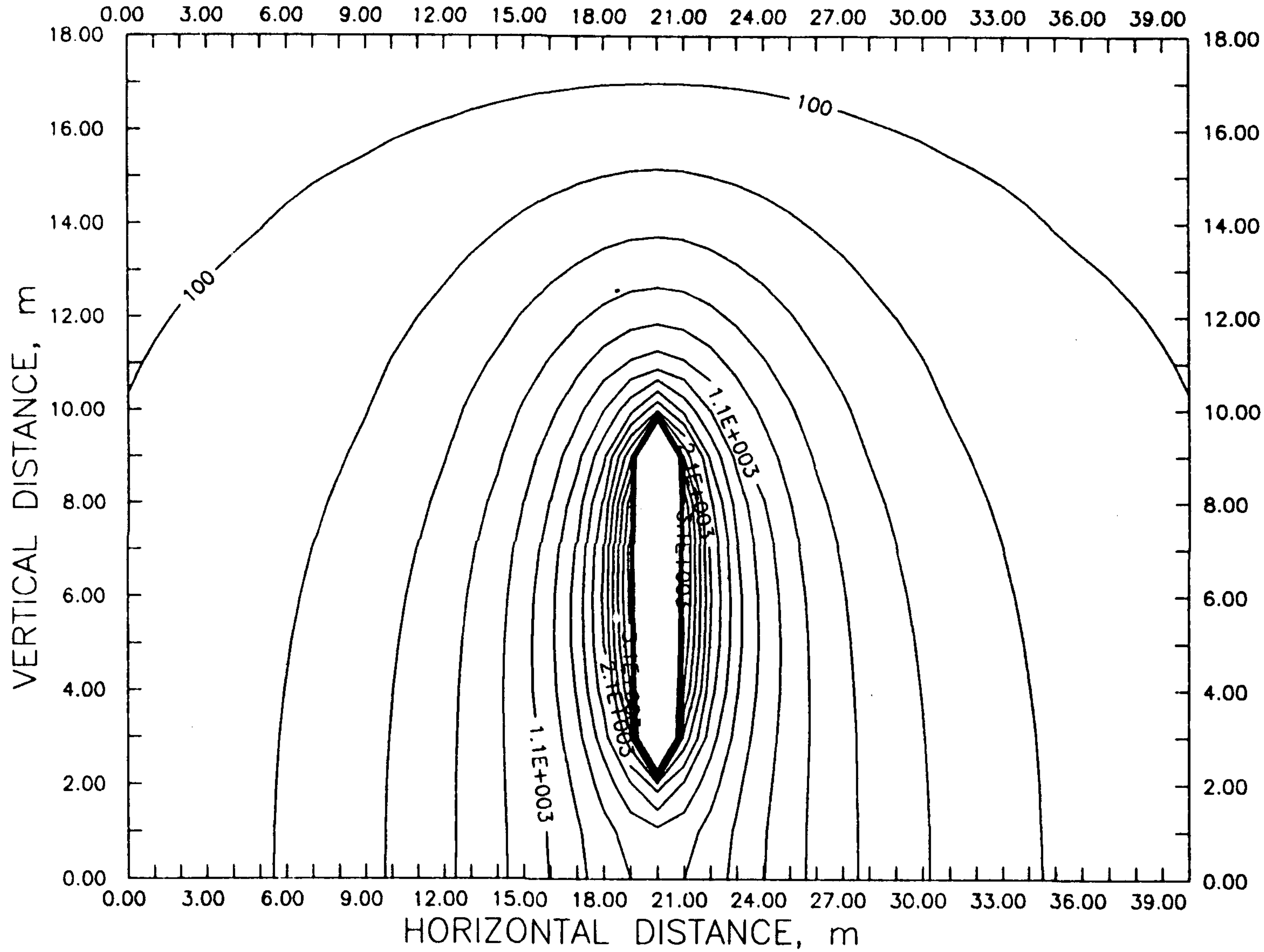

Figure E-2 (Frame 2). **FEMAIR Modelling Results - Pressure Contours for Vent with Screen at 9-15 Meters; No Surface Barrier (Continued).**

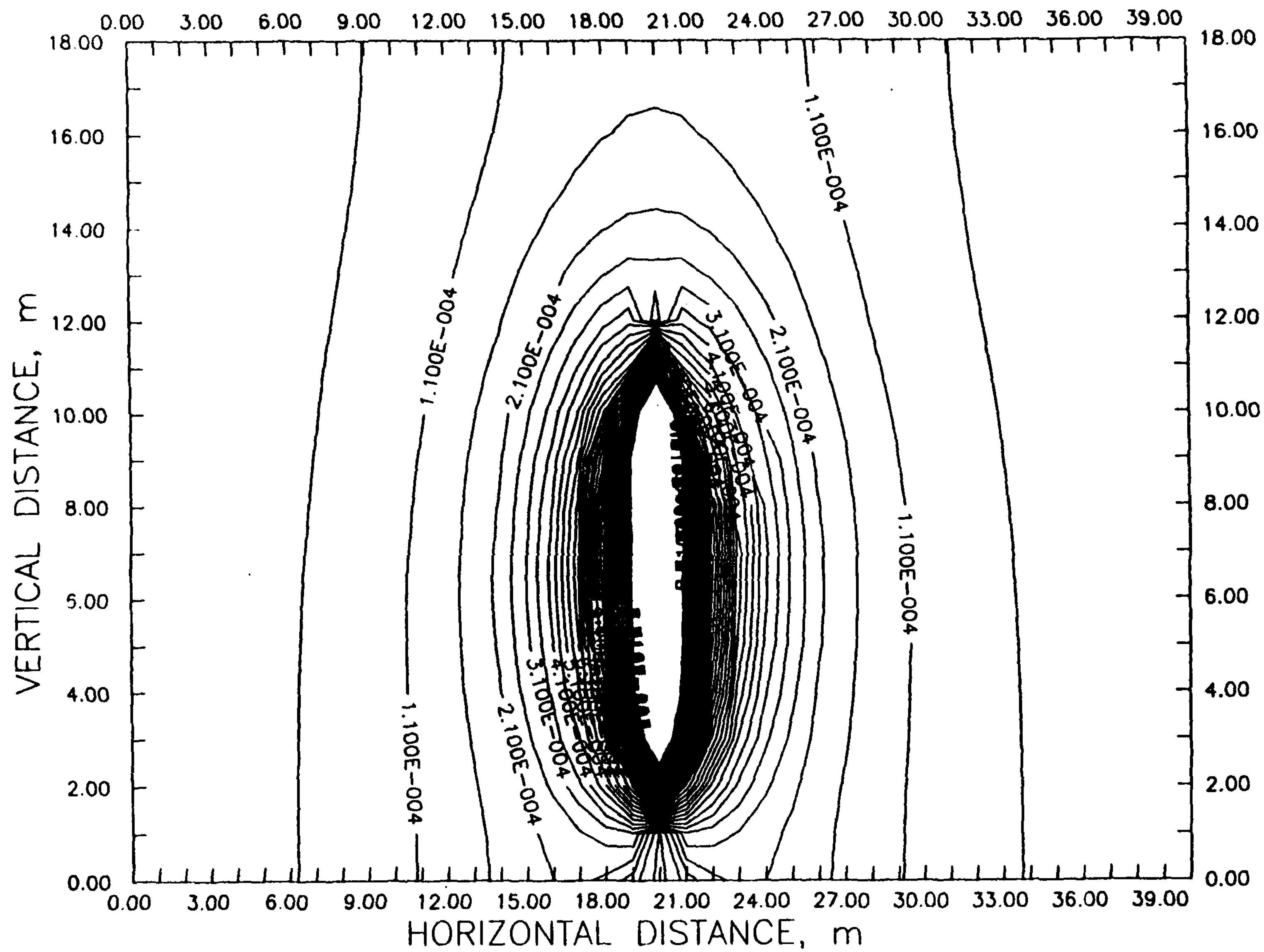

Figure E-2 (Frame 3). FEMAIR Modelling Results - Flow Contours for Vent with Screen at 9-15 Meters; No Surface Barrier (Concluded).

The cases presented in Figures E-3 through E-6 show situations similar to the previous two cases, but with surface barriers (simulated by a surface layer having a very low permeability) installed. For these cases, the flow has a greater horizontal component in all regions and fairly uniform cleanup over the area would be expected. Thus, some improvement over the cases with no surface barrier is provided if contamination is distributed further outward and deeper.

The situations presented by stratified soils are displayed in Figures E-7 through E-10. In Figures E-7 and E-8, the extraction well screen passes through a clay layer which has a thickness of 3 meters. In Figure E-8, a surface barrier is present. For both cases, there is very little flow in the clay layer, as expected, and the flow in the sand layer below the clay layer is reduced somewhat as compared to the layer above the clay. For the cases in Figures E-7 and E-8, the flow behavior in the top sand layer is similar to that of the cases in Figures E-1 and E-3, respectively.

In Figure E-9, the vent screen is located in a 3-meter clay layer. Consequently, there is relatively little flow in the clay or the sand layers. In Figure E-10, a clay layer extends from the surface to a depth of 9 meters. The screen extends through both the sand and clay layer and, as expected, flow exists primarily in the sand layer. For these situations in which clay layers are present, air injection wells extending into contaminated layers below the clay would be recommended.

When contamination exists over a large area, multiple vents will be operated. If the operating vents are sufficiently close to one another, their flow fields will overlap. As seen in Figure E-11 (the schematic for two wells is not shown, as it is readily visualized from Figure E-1), the vacuum between the two vents is much greater than that at a corresponding radial distance on the outside of the vents.

These vacuum and flow predictions from calculations with the FEMAIR model should be useful in designing venting wells. By understanding the flow behavior obtained under various conditions and configurations, one should be better able to tailor vent placement to effect efficient removal of contamination by ISSV.

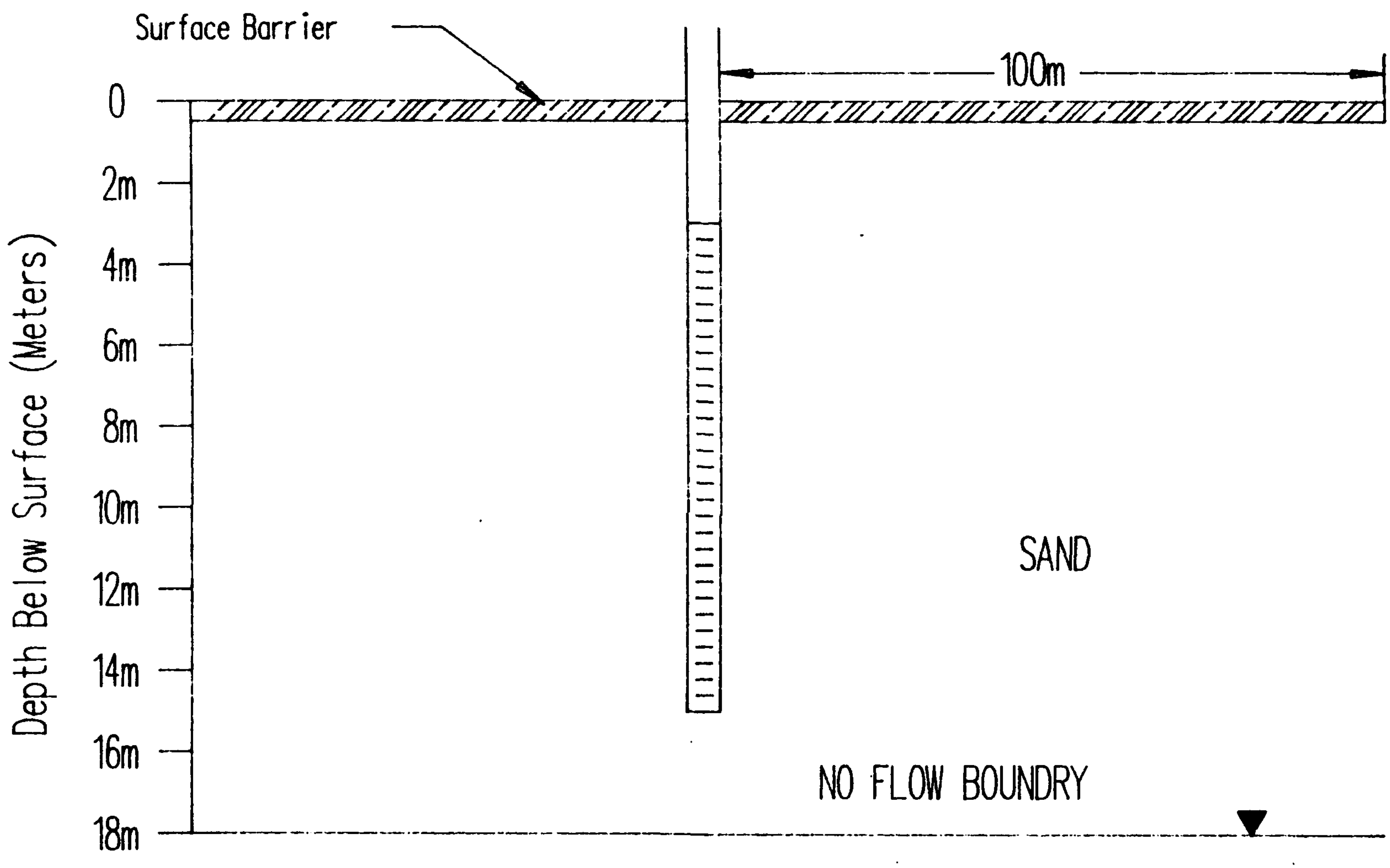

Figure E-3 (Frame 1). FEMAIR Modelling Results - Vent with Screen at 3-15 Meters and Extensive Surface Barrier.

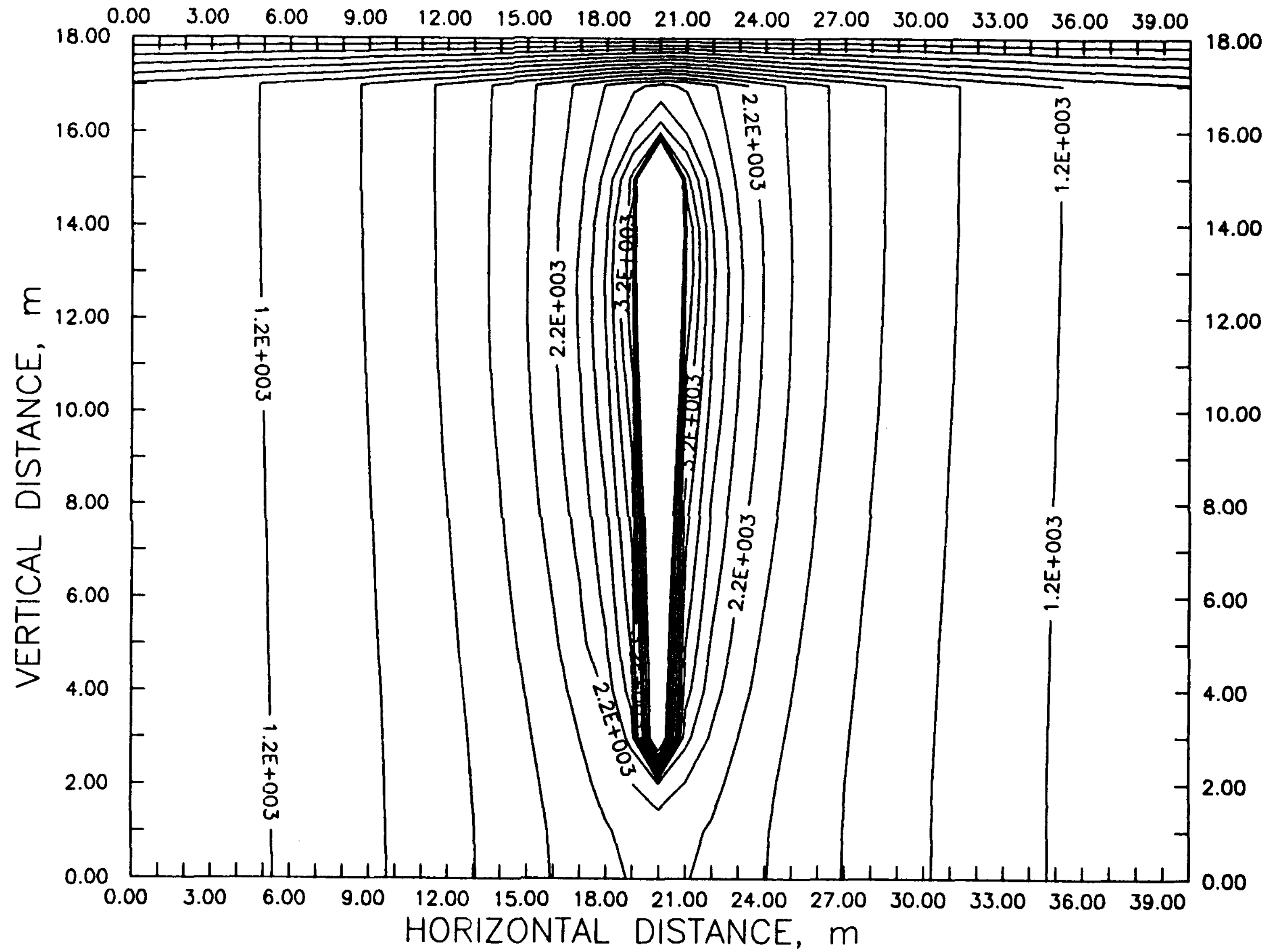

Figure E-3 (Frame 2). FEMAIR Modelling Results - Pressure Contours for Vent with Screen at 3-15 Meters and Extensive Surface Barrier (Continued).

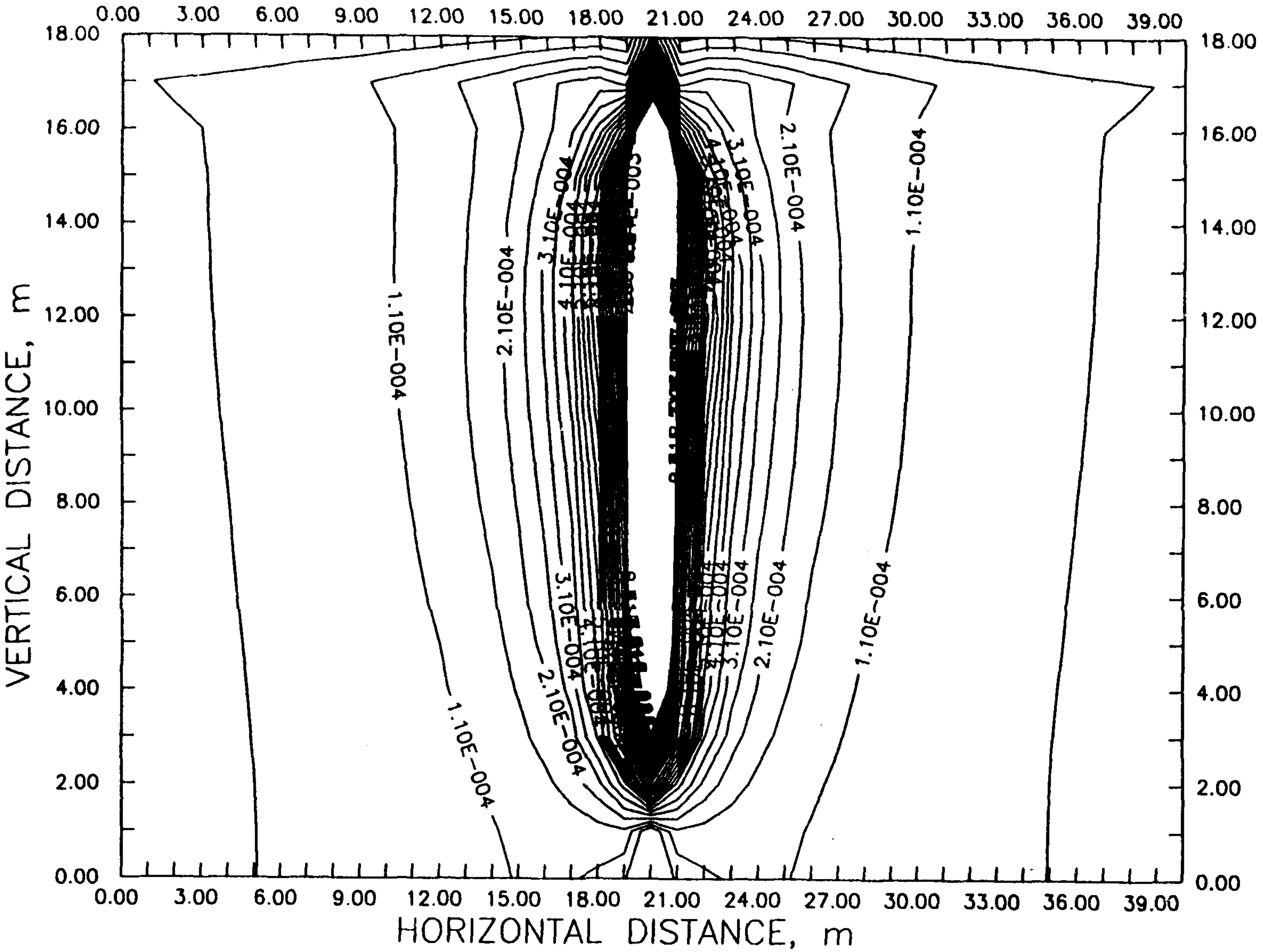

Figure E-3 (Frame 3). **FEMAIR Modelling Results - Flow Contours for Vent with Screen at 3-15 Meters and Extensive Surface Barrier (Concluded).**

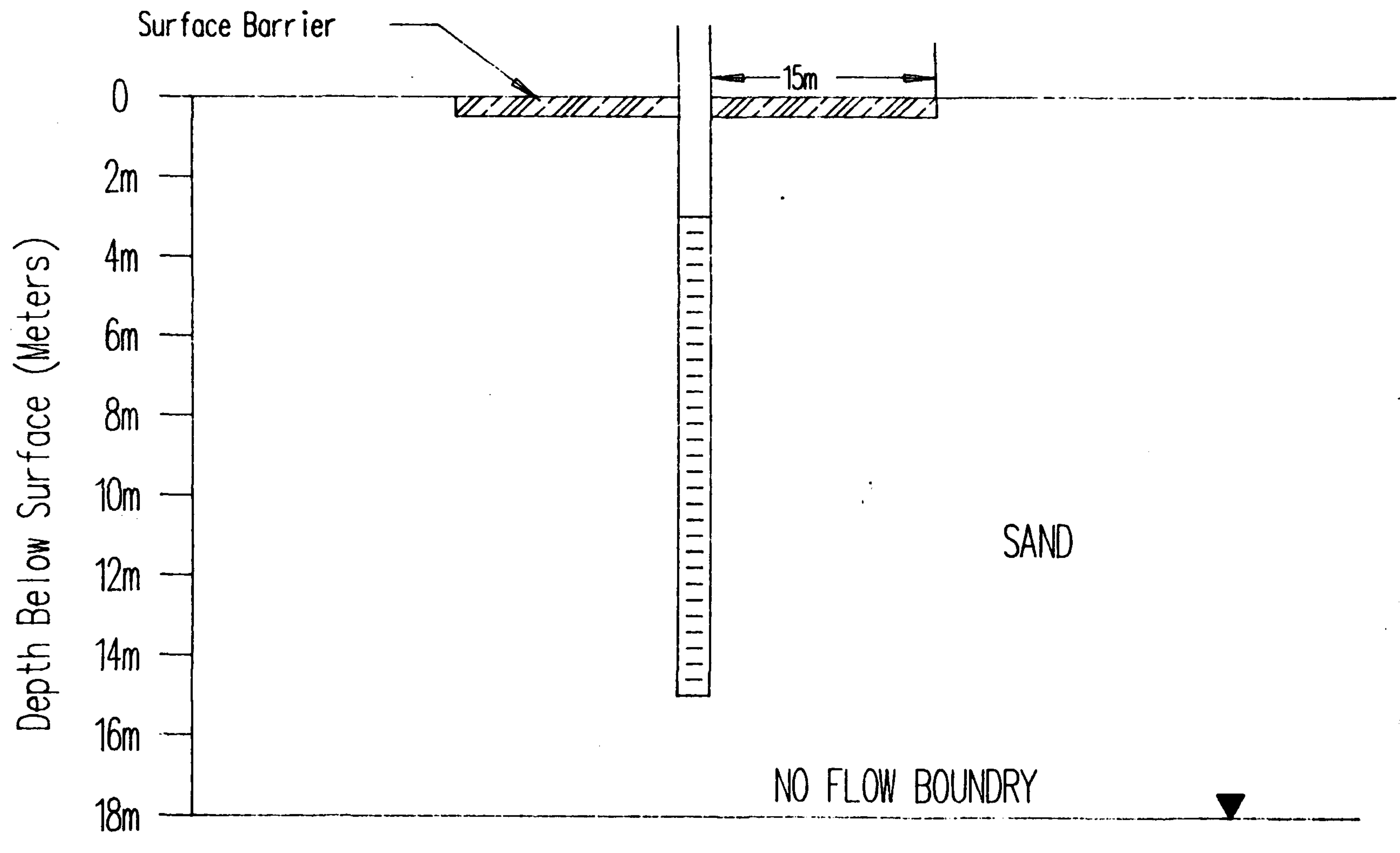

Figure E-4 (Frame 1). FEMAIR Modelling Results - Vent with Screen at 3-15 Meters and Limited Surface Barrier.

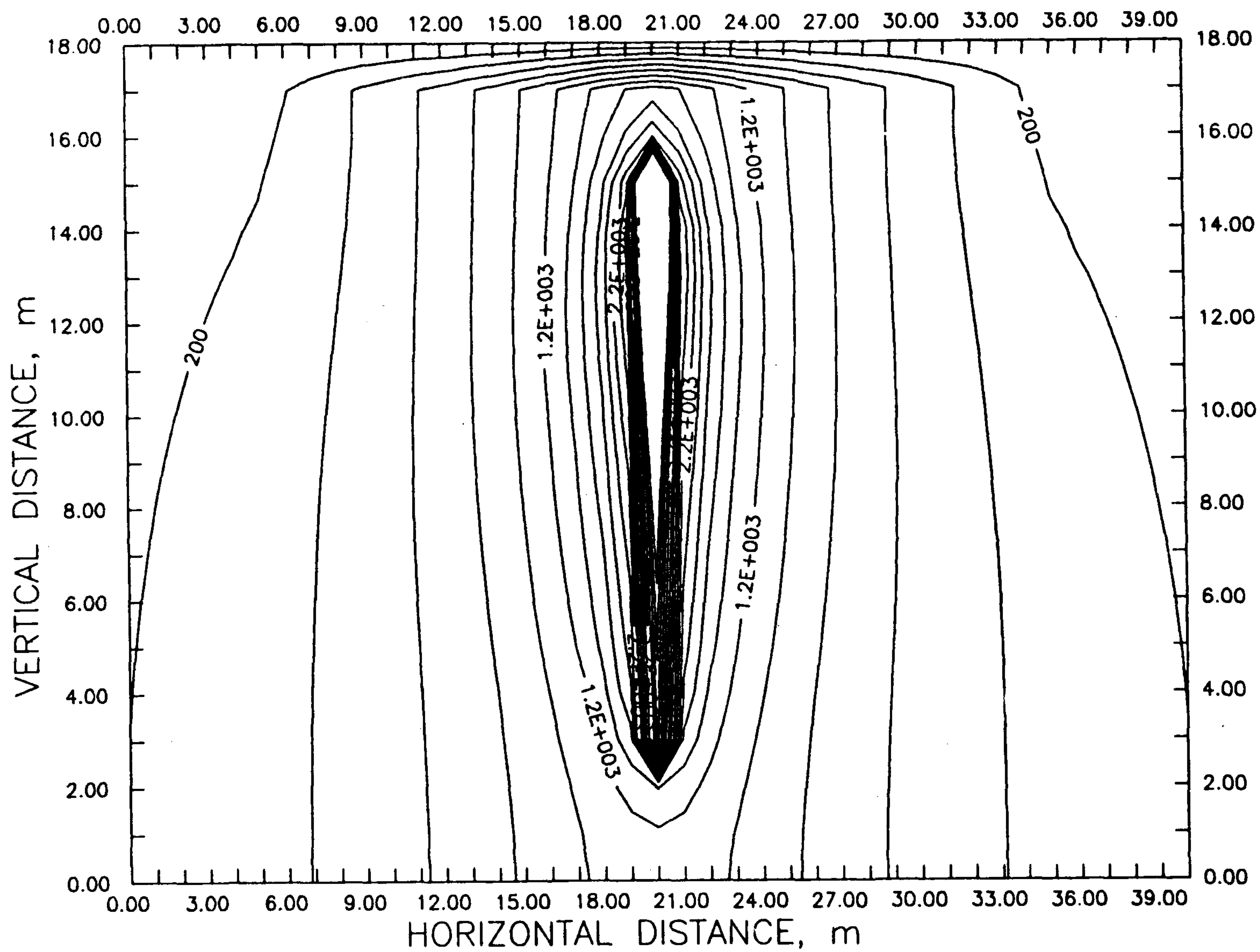

Figure E-4 (Frame 2). FEMAIR Modelling Results - Pressure Contours for Vent with Screen at 3-15 Meters and Limited Surface Barrier (Continued).

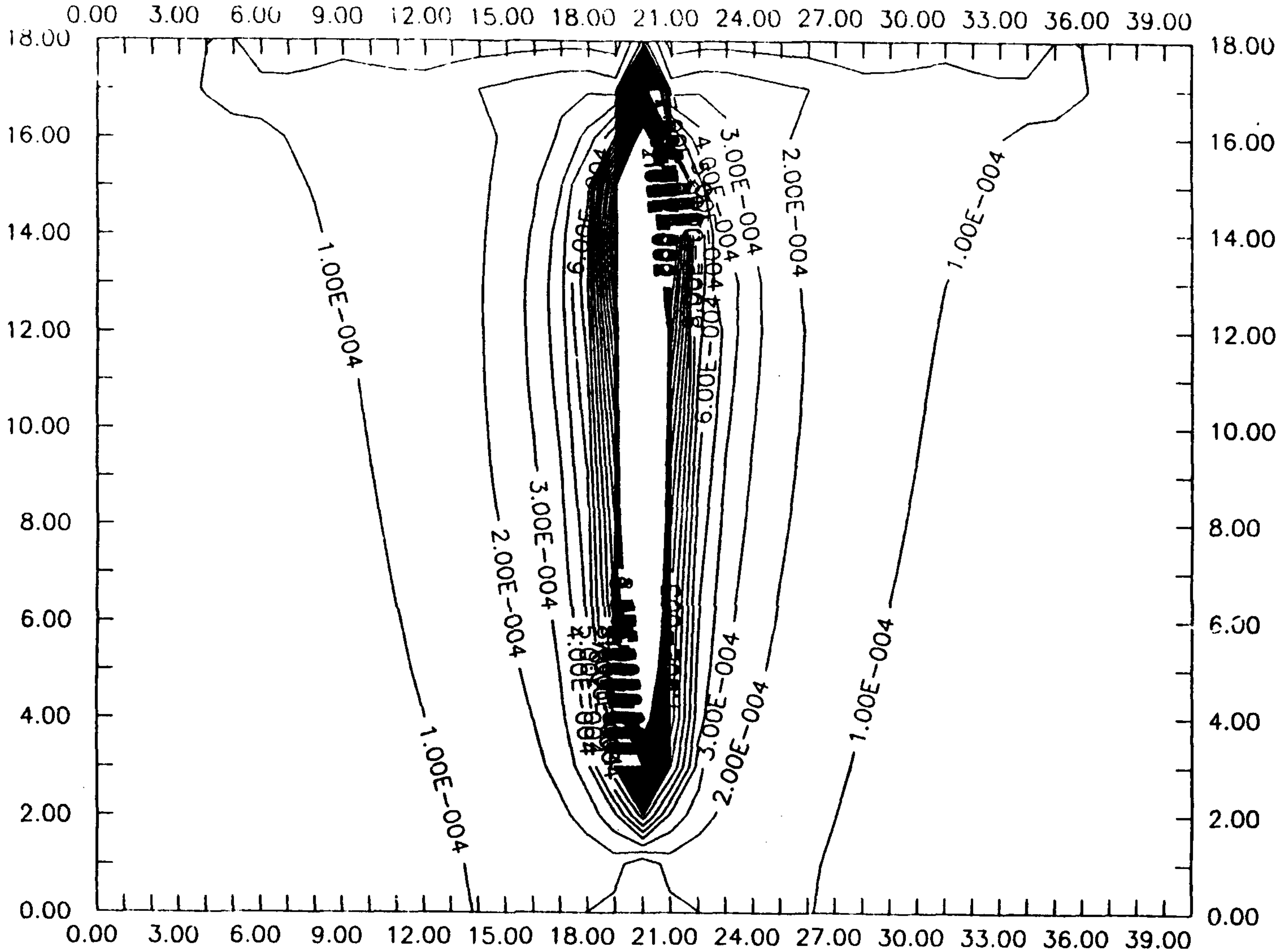

Figure E-4 (Frame 3). **FEMAIR Modelling Results - Flow Contours for Vent with Screen at 3-15 Meters and Limited Surface Barrier (Concluded).**

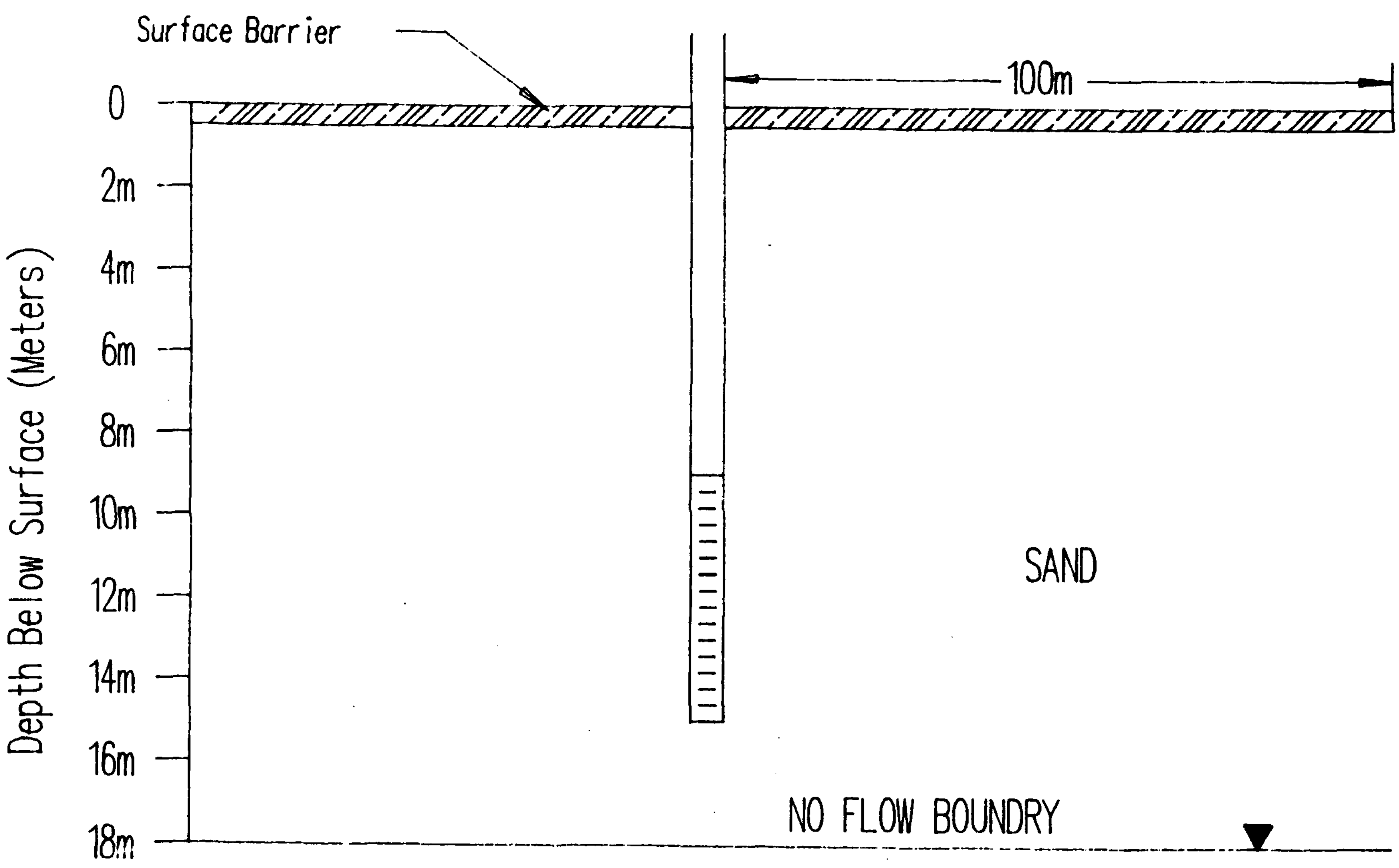

Figure E-5 (Frame 1). FEMAIR Modelling Results - Vent with Screen at 9-15 Meters and Extensive Surface Barrier.

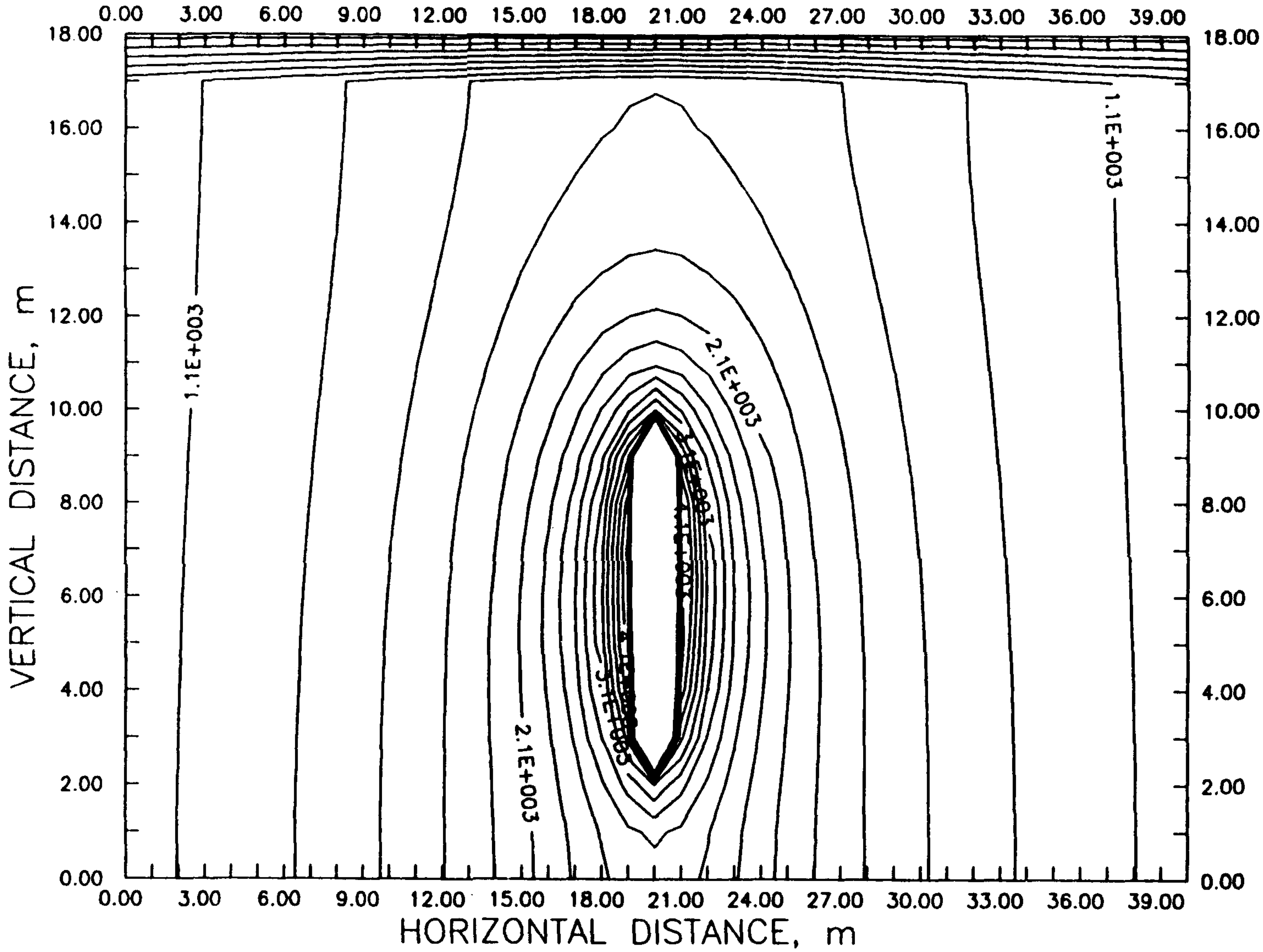

Figure E-5 (Frame 2). FEMAIR Modelling Results - Pressure Contours for Vent with Screen at 9-15 Meters and Extensive Surface Barrier (Continued).

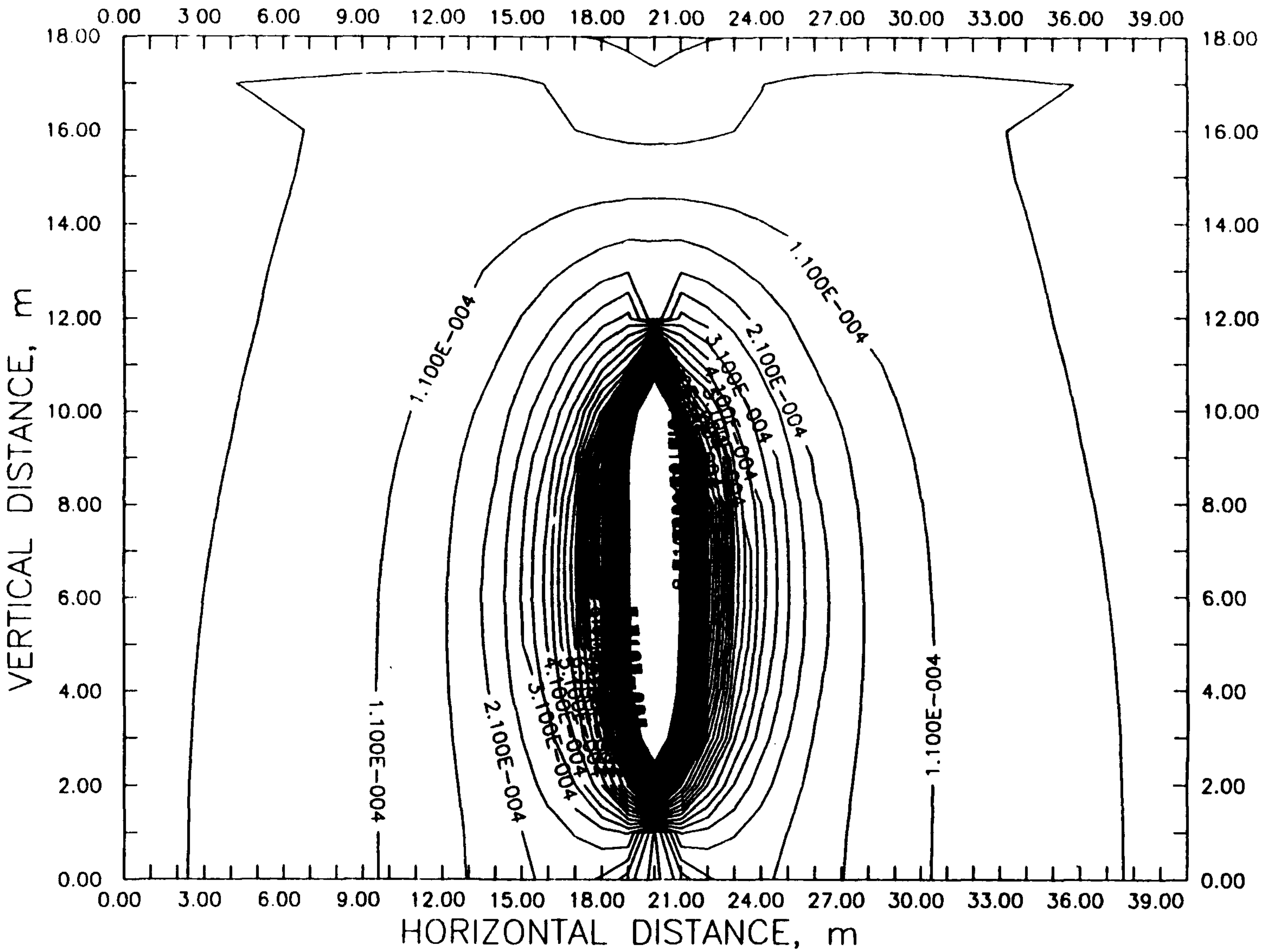

Figure E-5 (Frame 3). FEMAIR Modelling Results - Flow Contours for Vent with Screen at 9-15 Meters and Extensive Surface Barrier (Concluded).

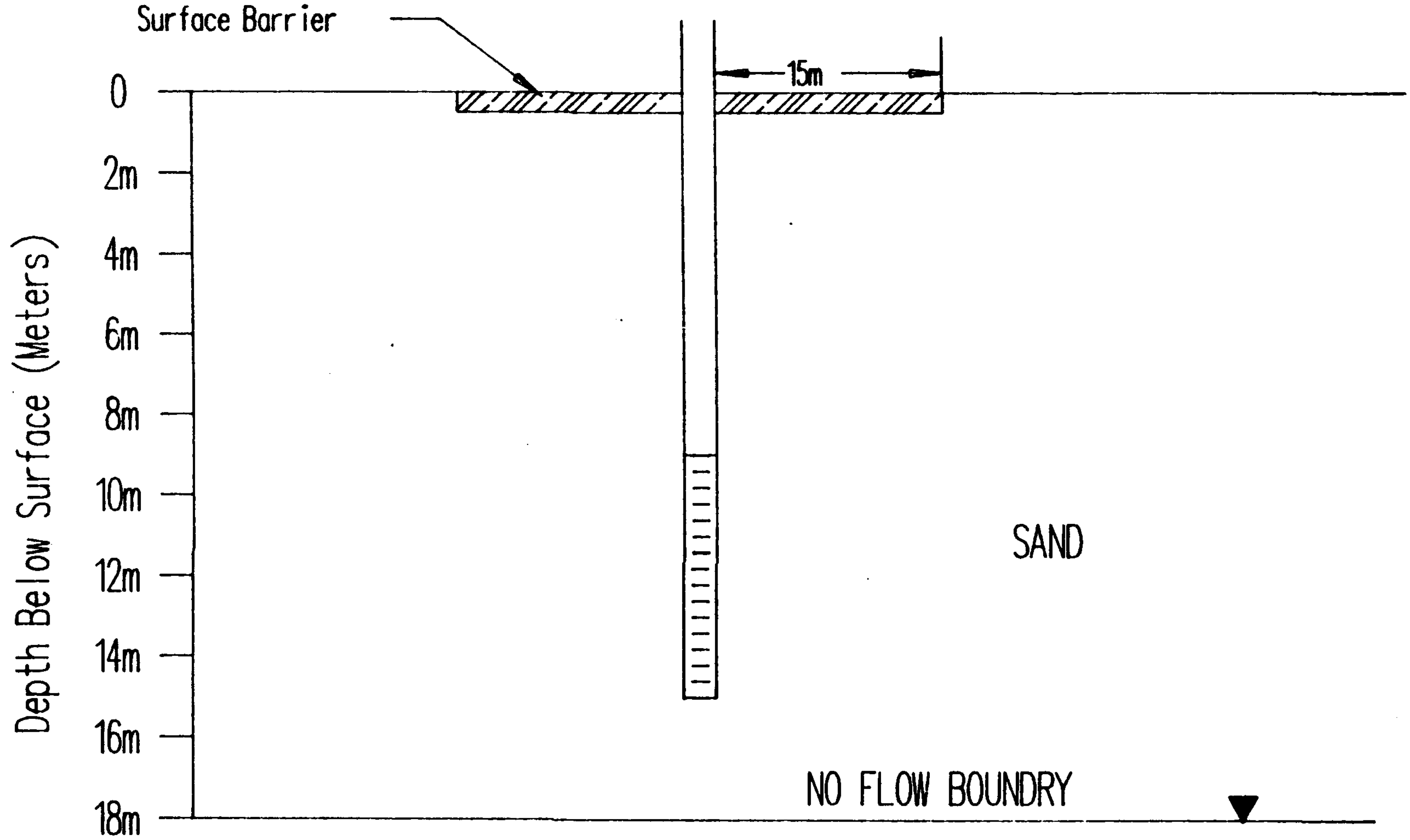

Figure E-6 (Frame 1). FEMAIR Modelling Results - Vent with Screen at 9-15 Meters and Limited Surface Barrier.

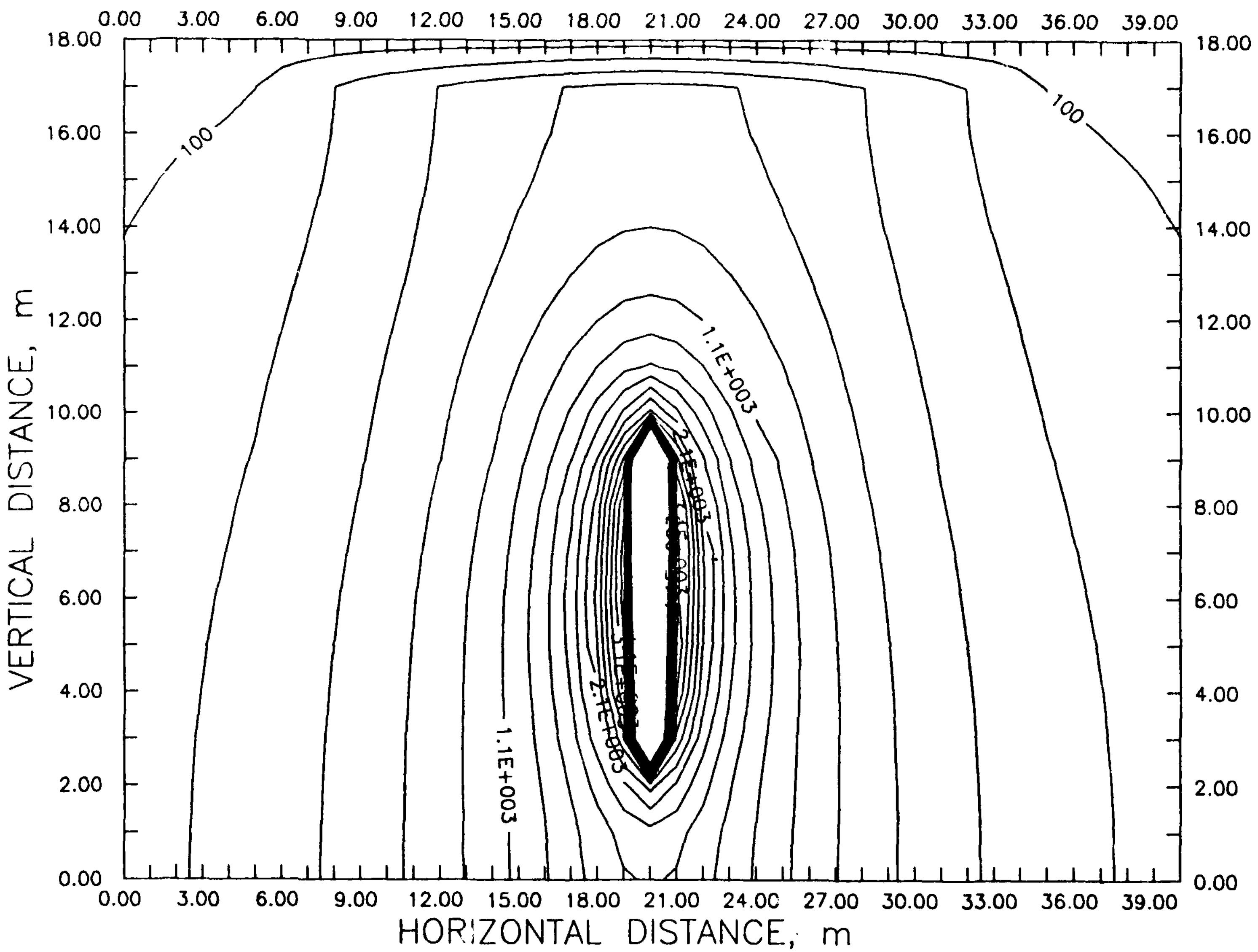

Figure E-6 (Frame 2). **FEMAIR Modelling Results - Pressure Contours for Vent with Screen at 9-15 Meters and Limited Surface** Barrier (Continued).

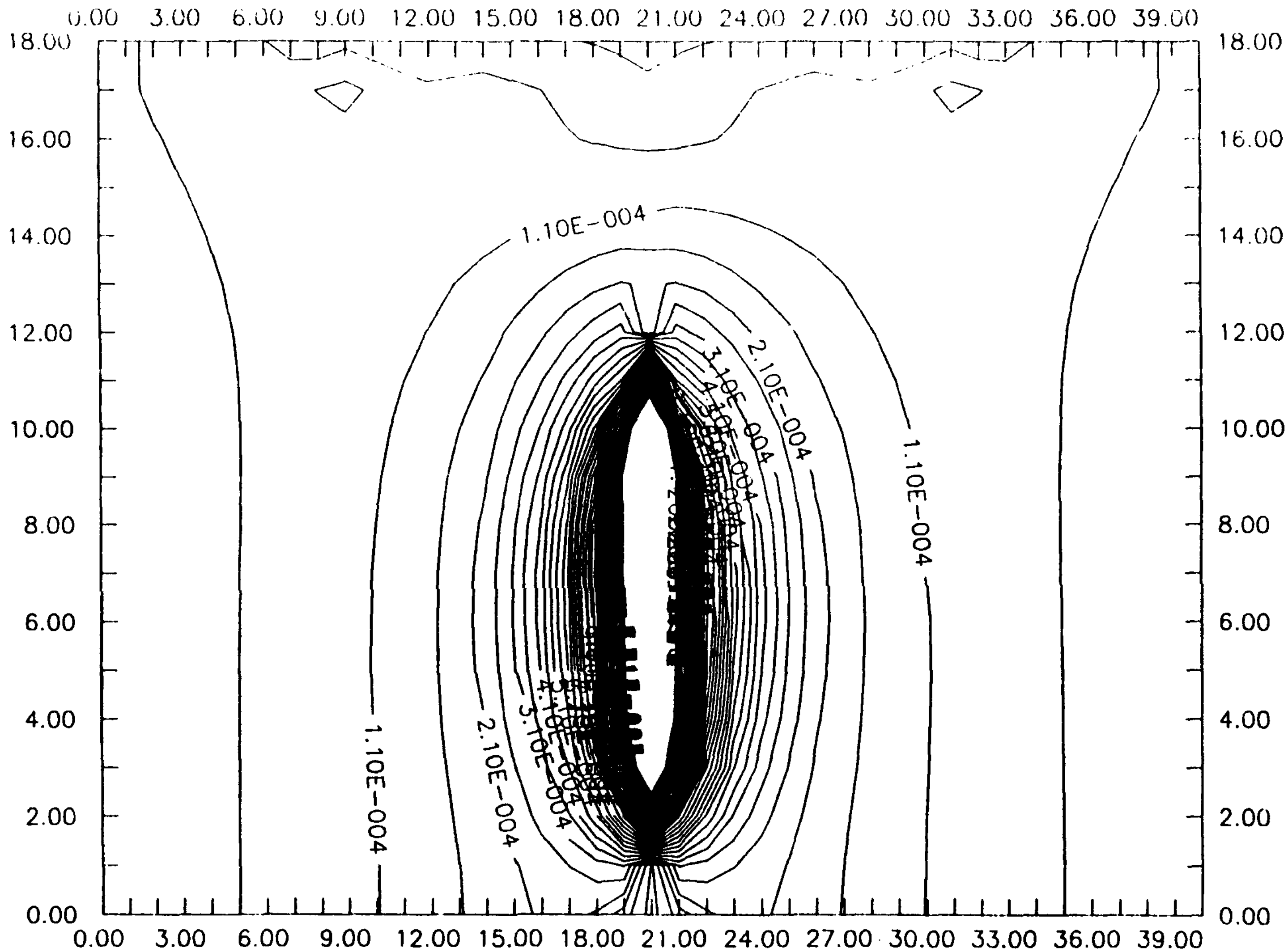

Figure E-6 (Frame 3). **FEMAIR Modelling Results - Flow Contours for Vent with Screen at 9-15 Meters and Limited Surface Barrier (Concluded).**

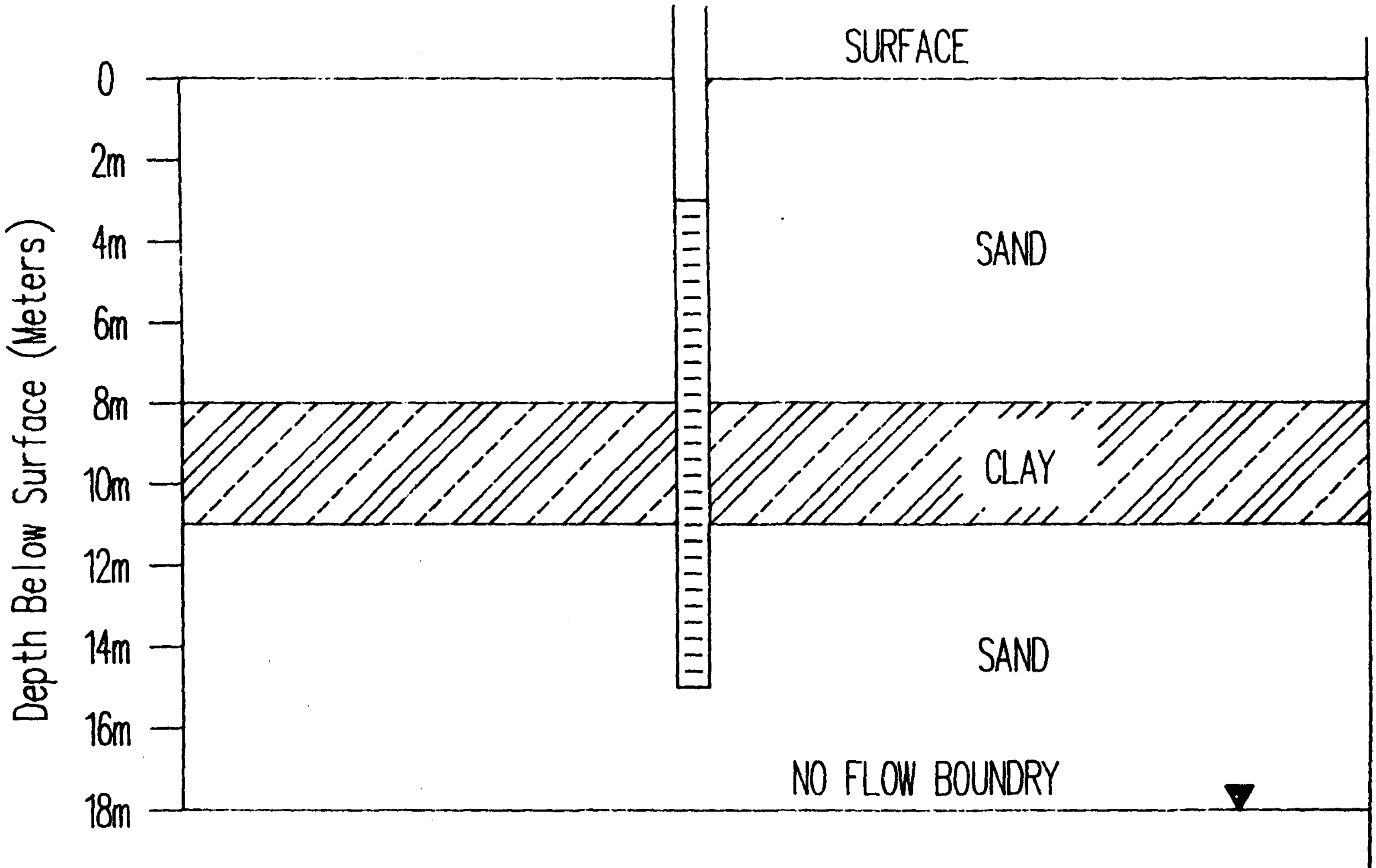

Figure E-7 (Frame 1). FEMAIR Modelling Results - Vent with Screen at 3-15 Meters and Clay Layer at 8-11 Meters; No Surface Barrier.

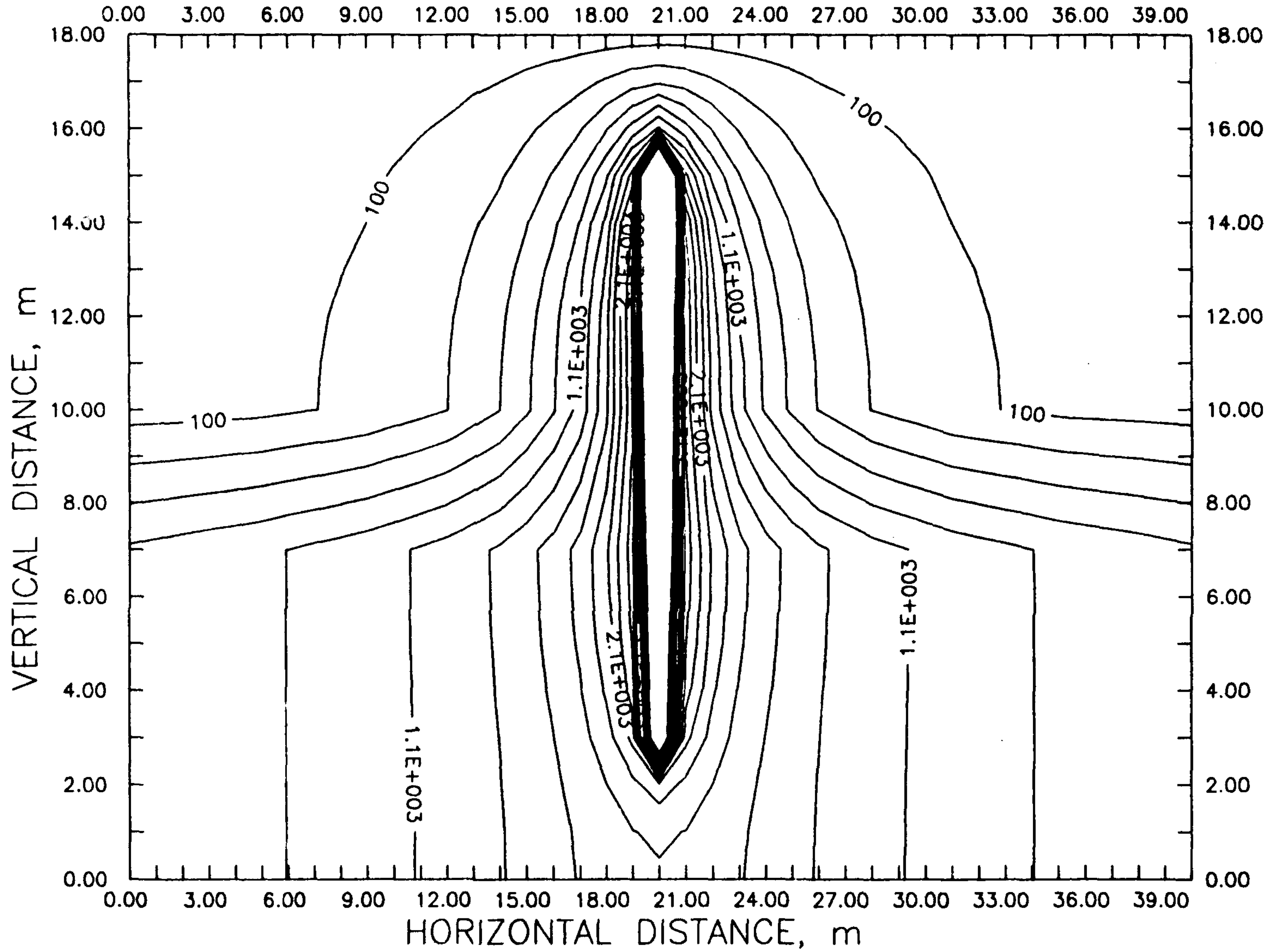

Figure E-7 (Frame 2). FEMAIR Modelling Results - Pressure Contours for Vent with Screen at 3-15 Meters and Clay Layer at 8-11 Meters; No Surface Barrier (Continued).

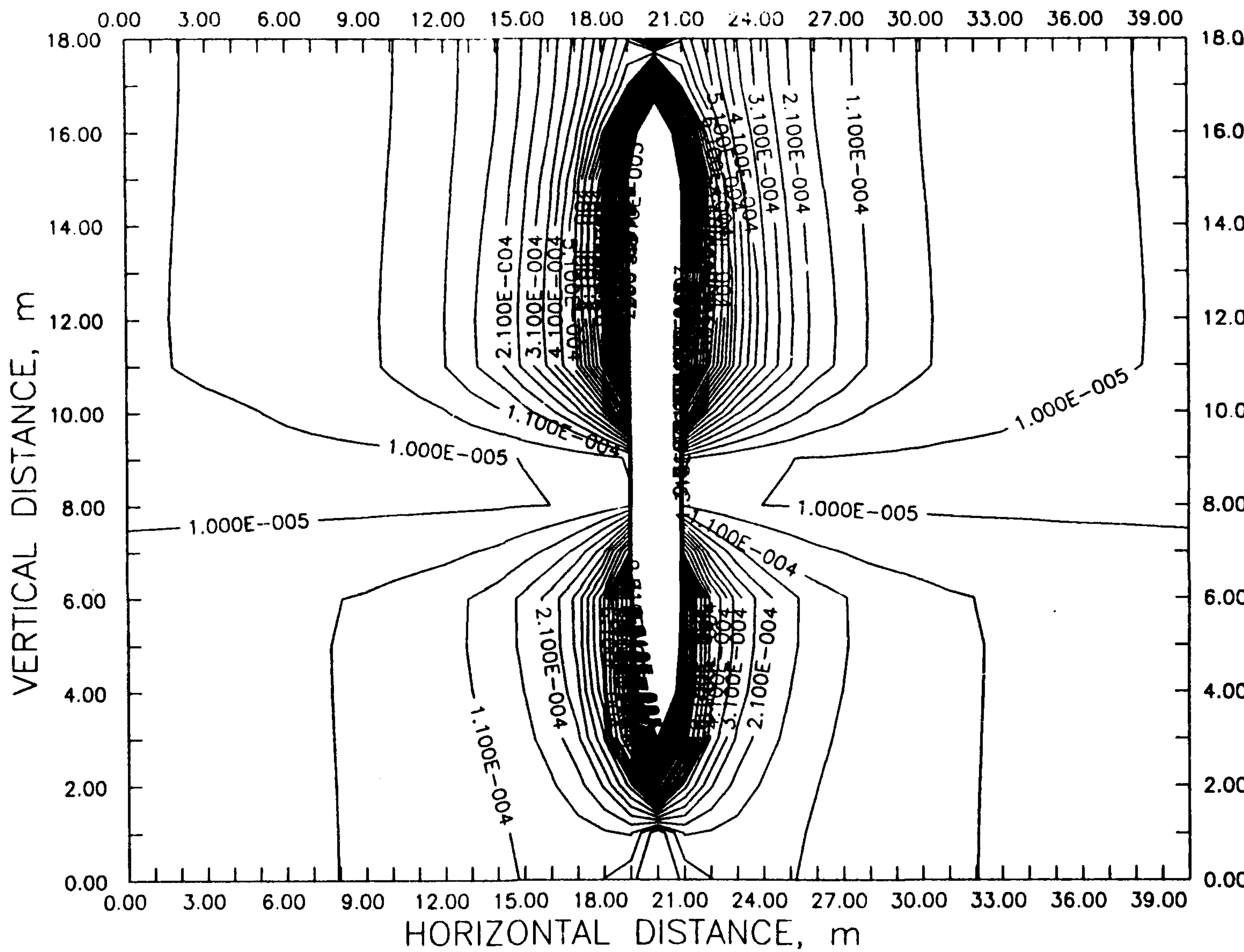

Figure E-7 (Frame 3). FEMAIR Modelling Results - Flow Contours for Vent with Screen at 3-15 Meters and Clay Layer at 8-11 Meters; No Surface Barrier (Concluded).

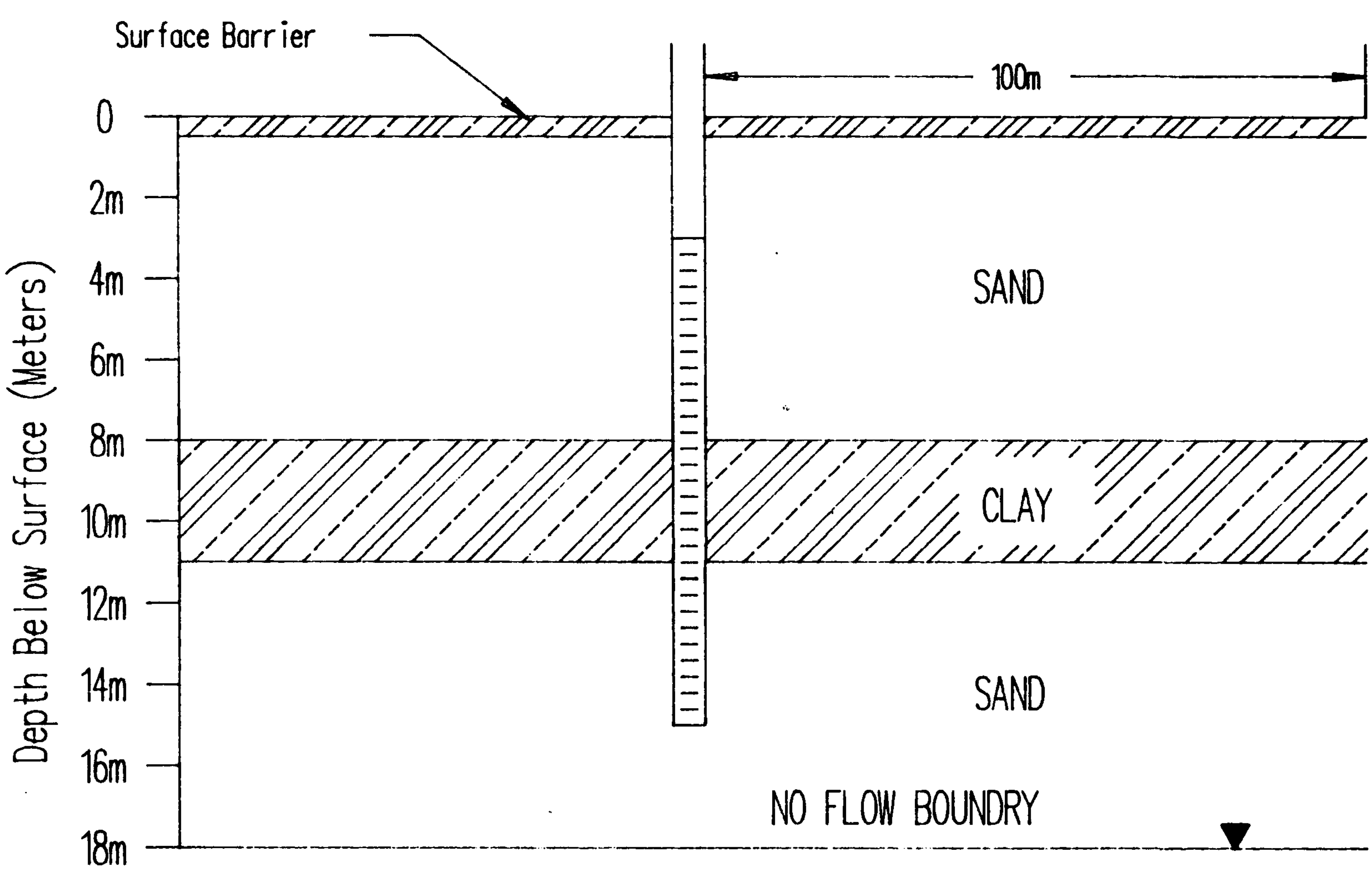

Figure E-8 (Frame 1). FEMAIR Modelling Results - Vent with Screen at 3-15 Meters, Clay Layer at 8-11 Meters, and Extensive Surface Barrier.

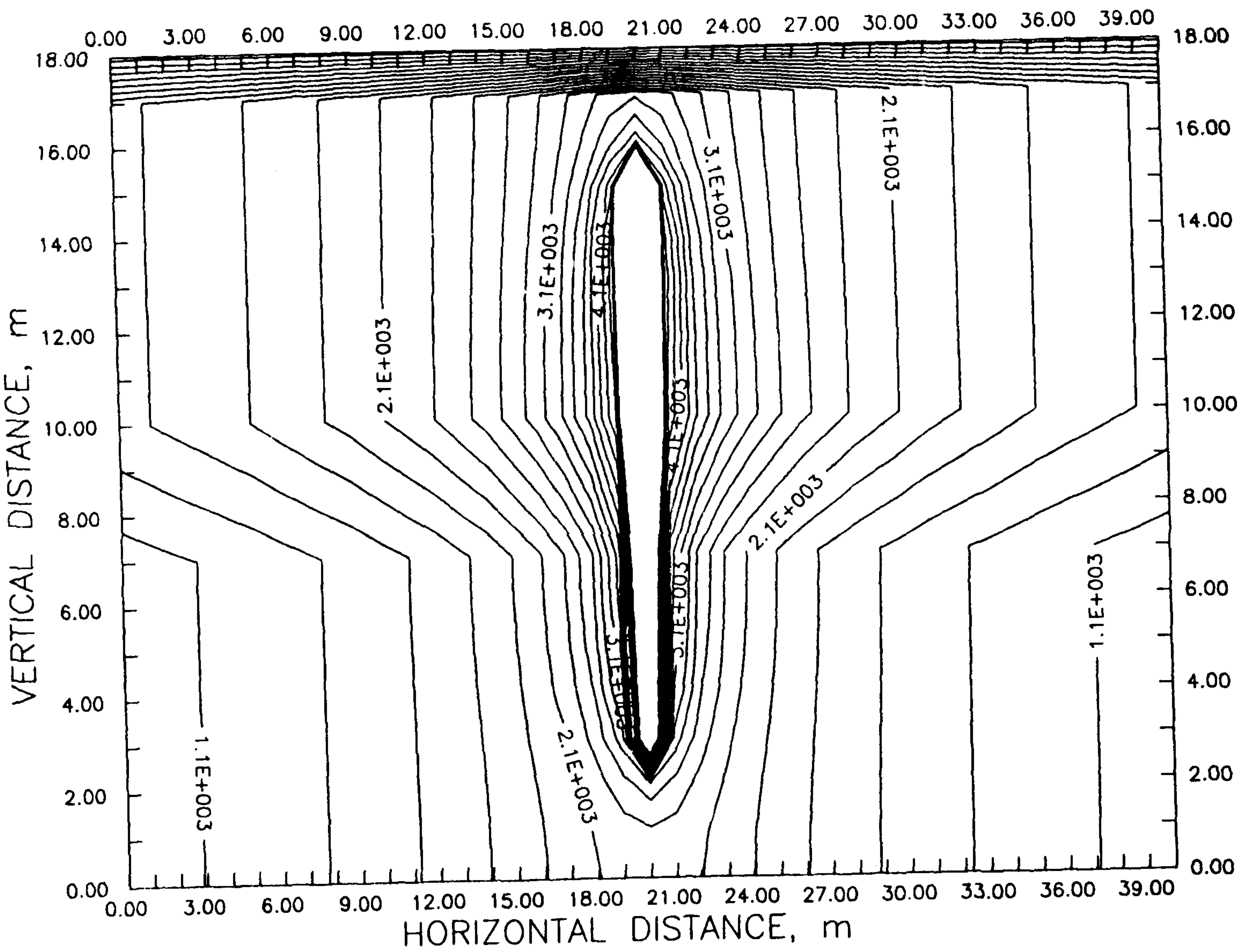

Figure E-8 (Frame 2). **FEMAIR Modelling Results** - **Pressure** *Contours* **for Vent with** *Screen* **at 3-15 Meters, Clay Layer at 8-11 Meters, and Extensive Surface Barrier (Continued).**

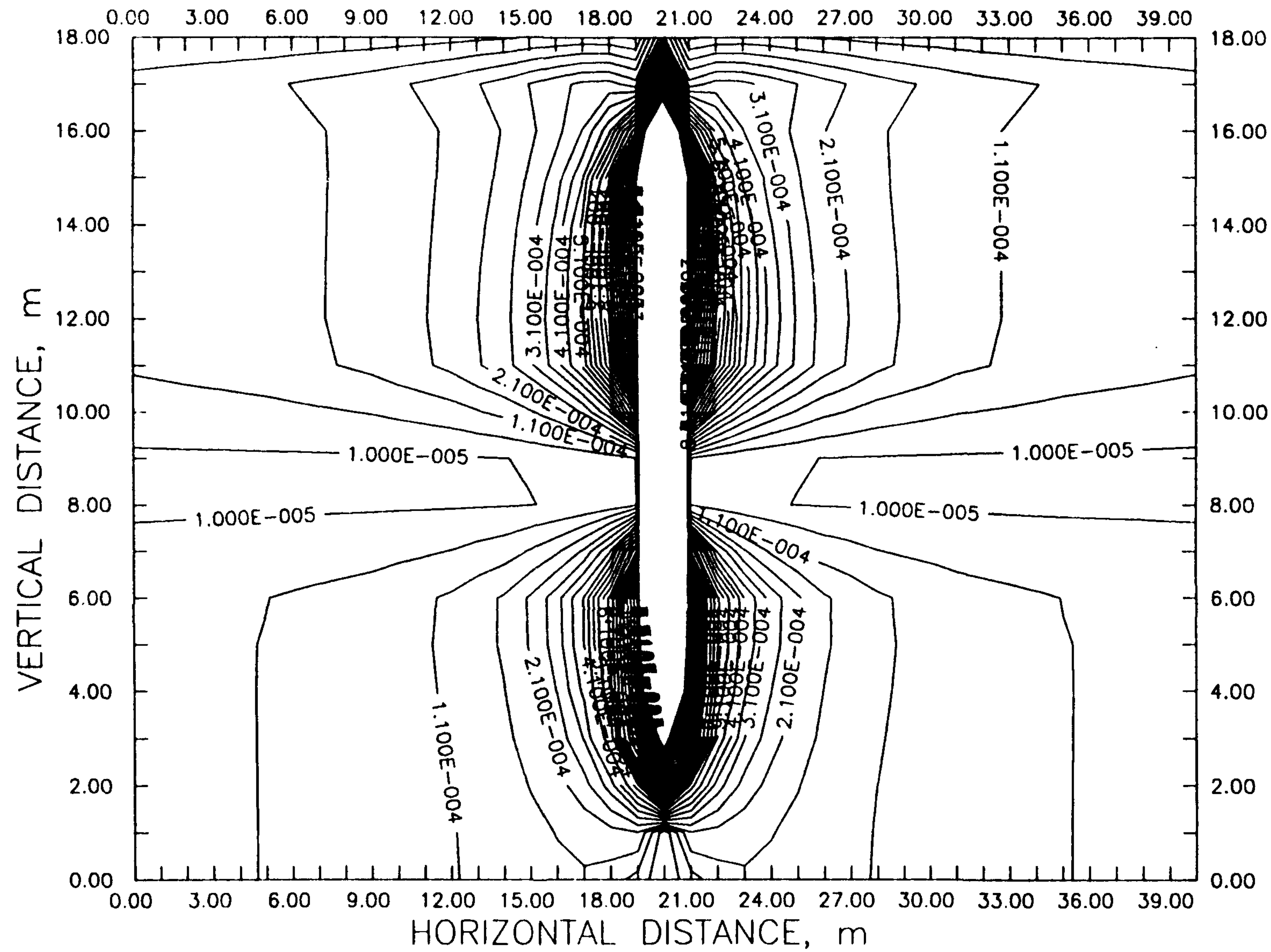

Figure E-8 (Frame 3). FEMAIR Modelling Results - Flow Contours for Vent with Screen at 3-15 Meters, Clay Layer at 8-11 Meters, and Extensive Surface Barrier (Concluded).

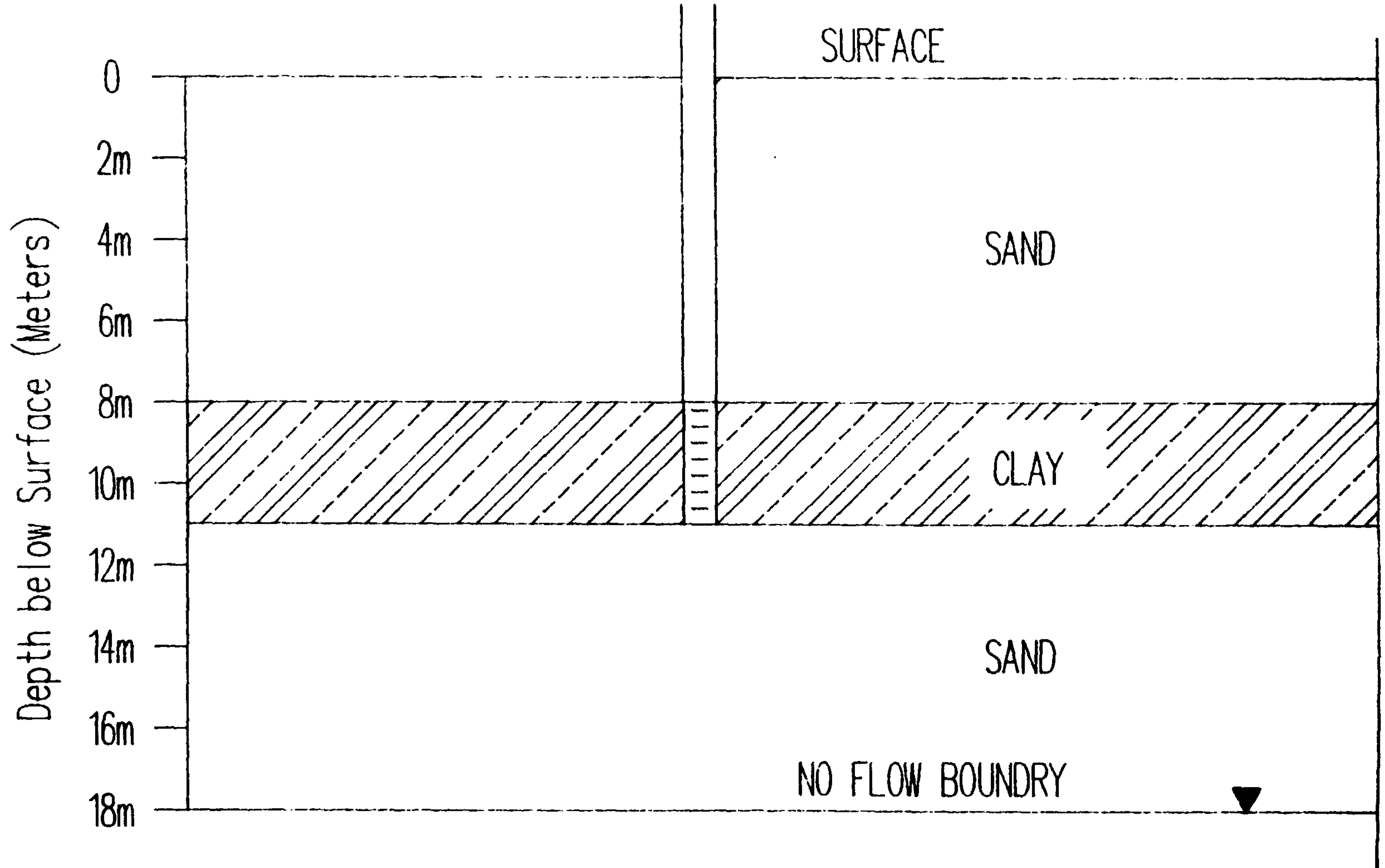

Figure E-9 (Frame 1). FEMAIR Modelling Results - Vent with Screen at 8-11 Meters in Clay Layer; No Surface Barrier.

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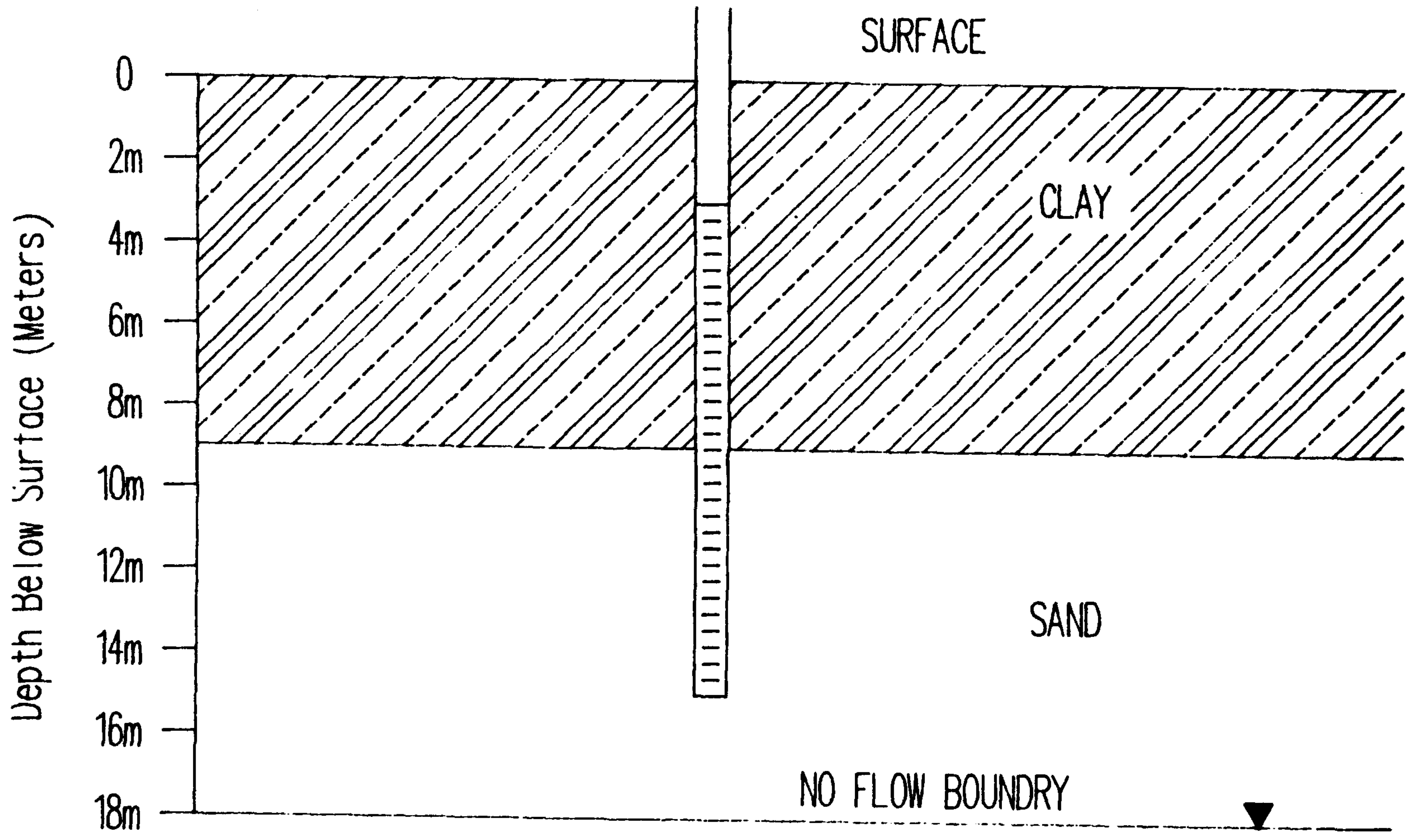

Figure E-10 (Frame 1). FEMAIR Modelling Results - Vent with Screen at 3-15 Meters and Clay Layer from Surface to 9 Meters.

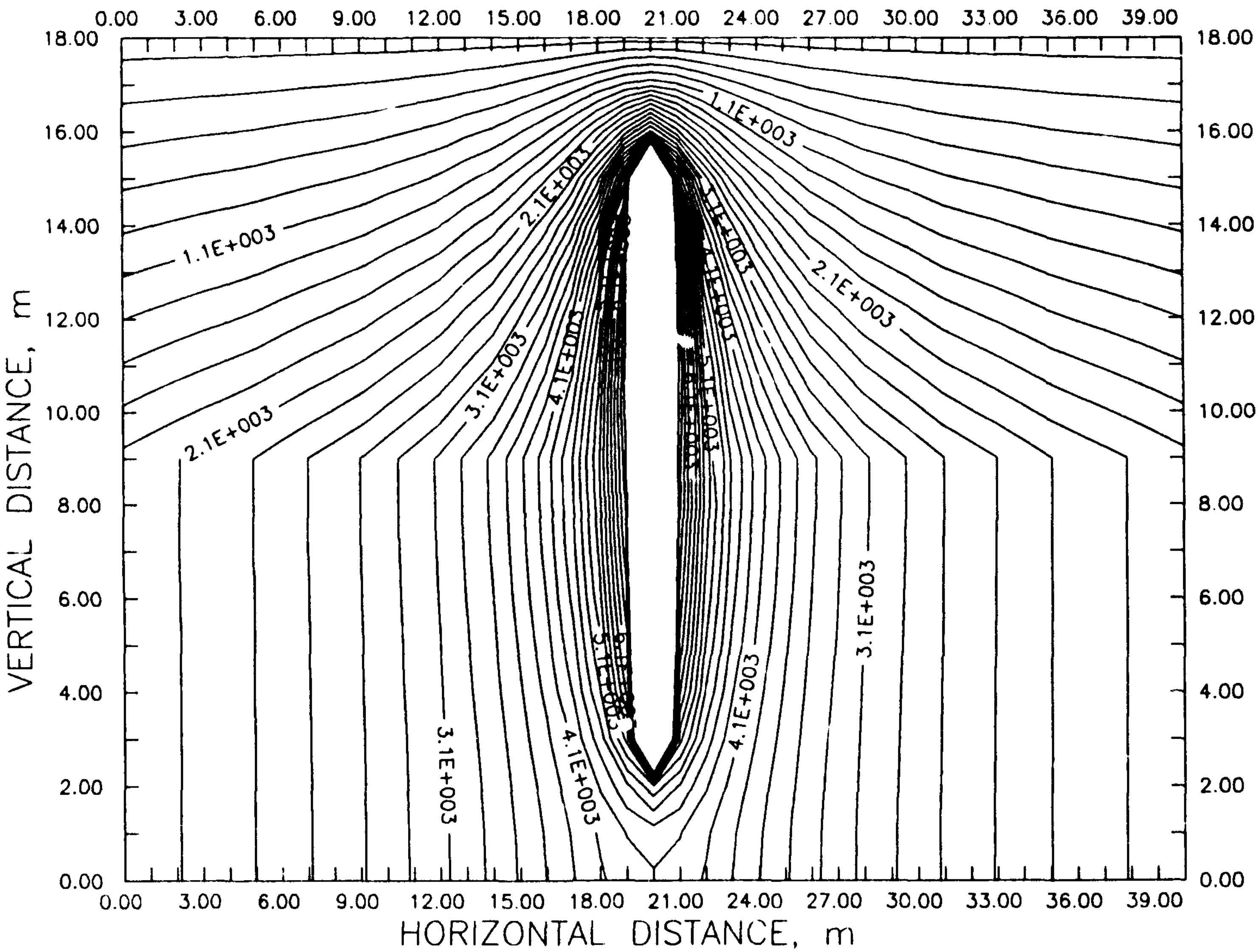

Figure E-10 (Frame 2). FEMAIR Modelling Results - Pressure Contours for Vent with Screen at 3-15 Meters and Clay Layer from Surface to 9 Meters (Continued).

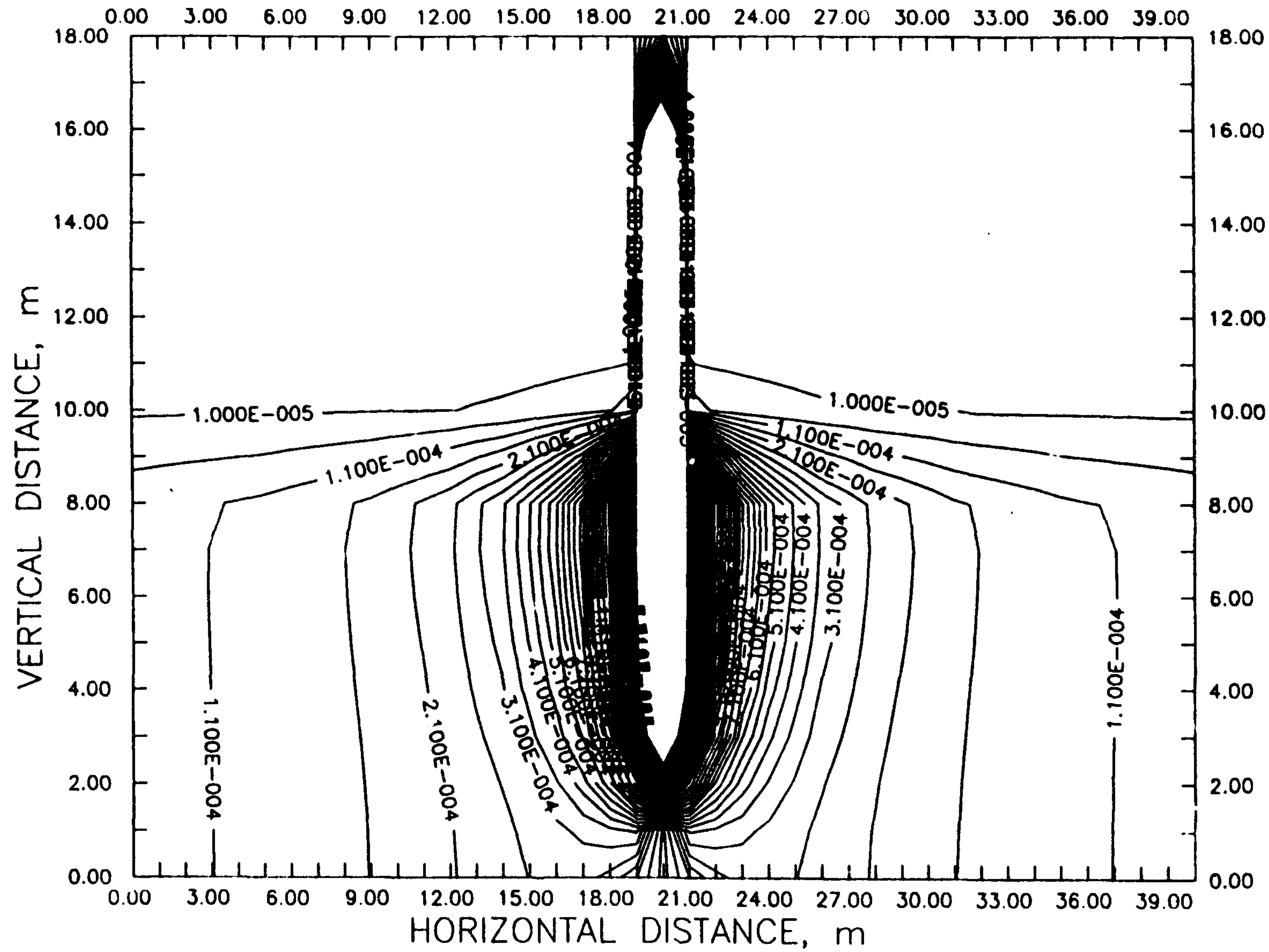

Figure E-10 (Frame 3). FEMAIR Modelling Results - Flow Contours for Vent with Screen at 3-15 Meters and Clay Layer from Surface to 9 Meters (Concluded).

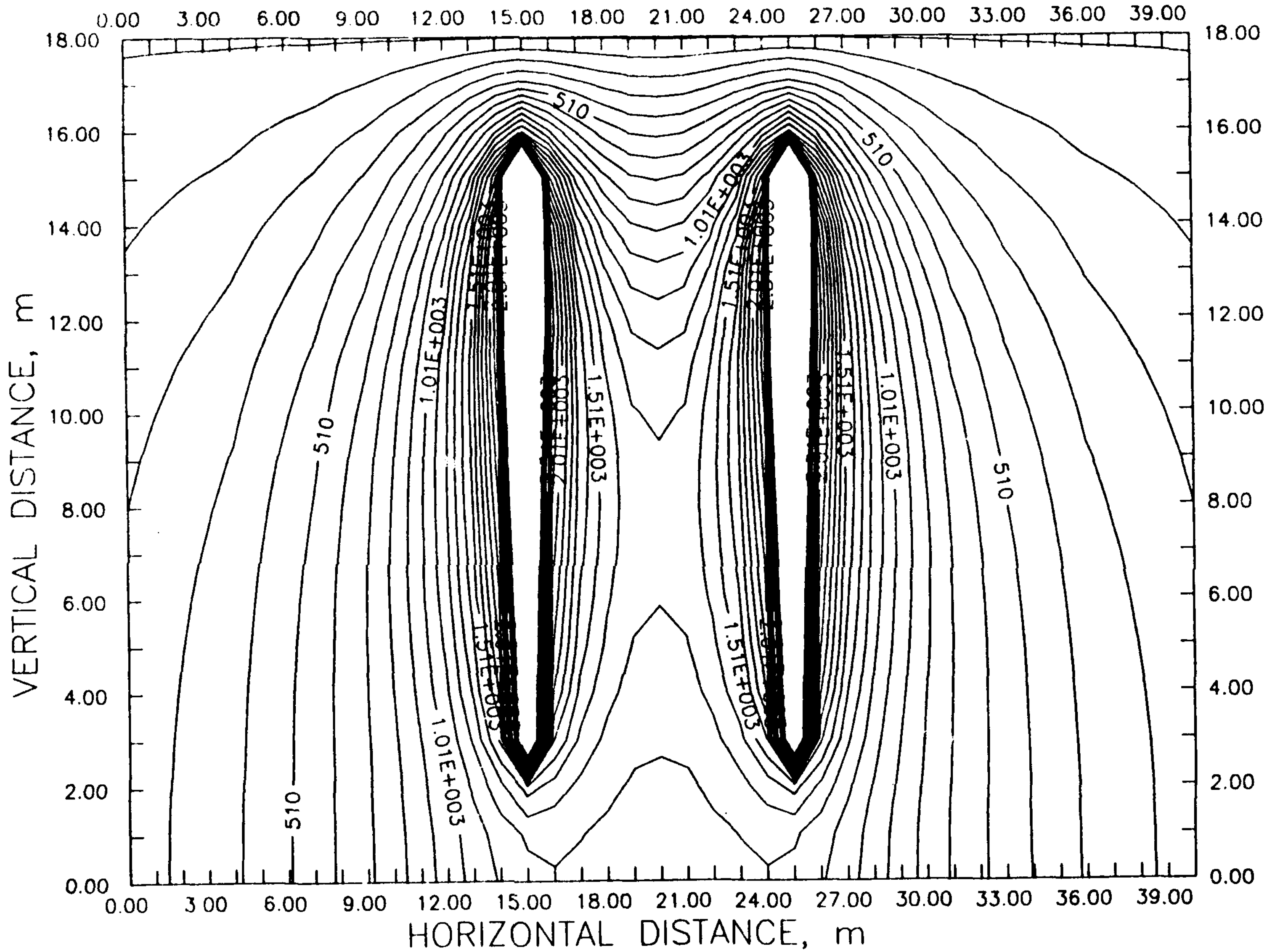

Figure E-11 (Frame 1). FEMAIR Modelling Results - Pressure Contours for Two Vents with Screens at 3-15 Meters; No Surface Barrier.

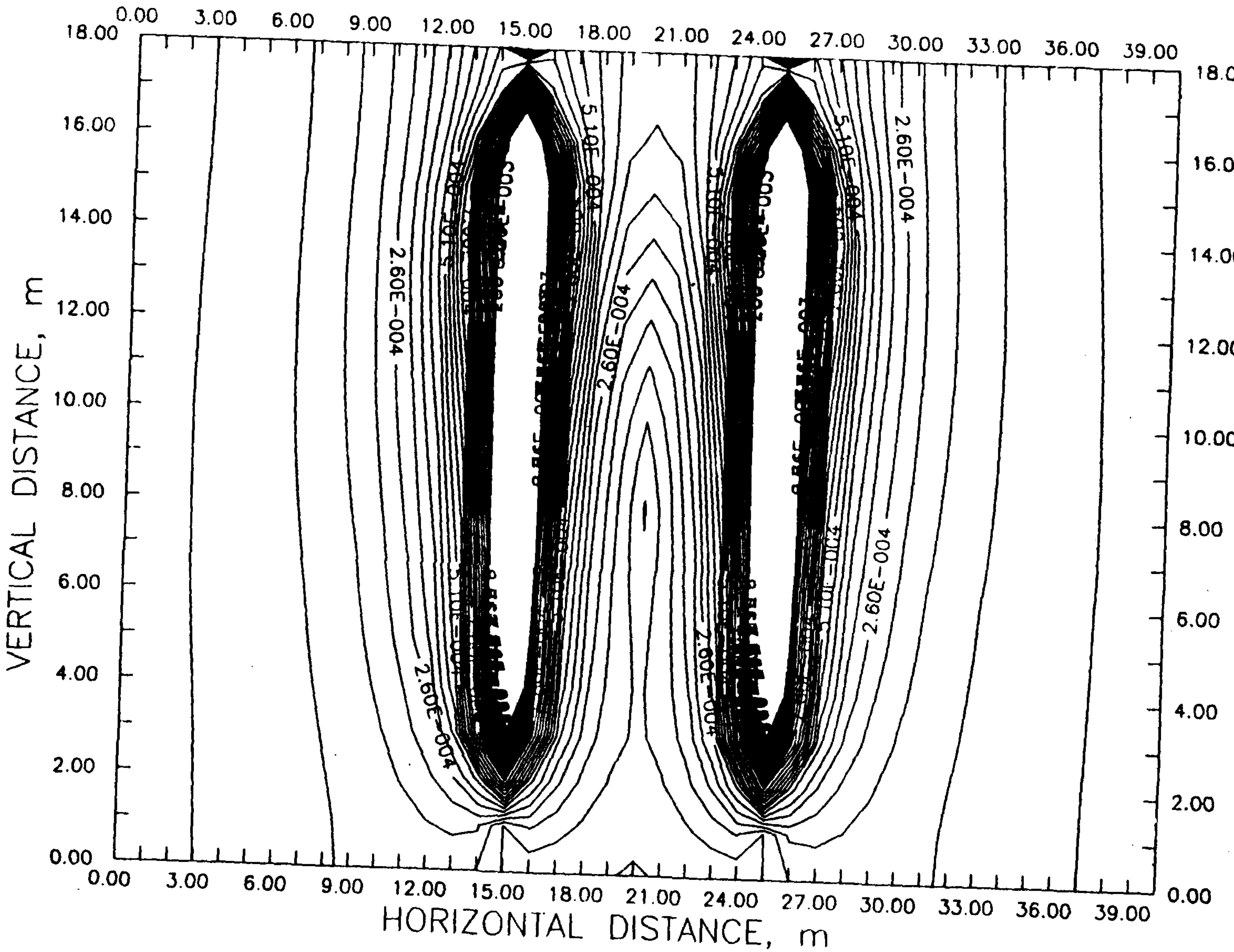

Figure E-11 (Frame 2). FEMAIR Modelling Results - Flow Contours for Two Vents with Screens at 3-15 Meters; No Surface Barrier (Concluded).

APPENDIX F

DESCRIPTION OF ECONOMETRIC MODEL

A. INTRODUCTION

The spreadsheet-based econometric model for ISSV is described in detail in this appendix. The model generates costs for three system configurations; (1) ISSV with no emissions control, (2) ISSV with off-gas treatment using catalytic oxidation, and (3) ISSV with off-gas treatment using activated carbon adsorption. These three options are believed to be the most common and feasible emissions control options. As discussed in Section VII, based upon physical and financial input parameters, the model calculates the capital costs of major equipment items and the total annual expense cost for the base year (1990 in all the examples presented herein). This analysis is performed in spreadsheet VENT-2.100. These costs are then used as input to a lifetime financial analysis model, in spreadsheet VENT-2.300, to produce a cost per pound of contaminant removed by the ISSV process. Instructions for running these spreadsheets are presented in Appendix G.

The operating lifetime analysis was used because capital and annual expense cost estimating alone is not adequate for the economic evaluation of a proposed project. In the case of manufacturing operations, an important step is to evaluate the unit manufacturing cost, e.g., the cost per unit of polyethylene produced by a manufacturing facility. However, no manufacturing is involved in the ISSV process. Consequently, the "standard" selected for complete cost evaluation of ISSV was the total current year dollar cost per pound of hydrocarbon contaminant removed from the ground. The determination of total current year cost involved (1) calculating the annual capital and expense costs for each year of operation and (2) summing these yearly costs. The expense cost for each year of the operating lifetime was calculated using the annual expense estimate for the base year, determined as described above, and adjusting it to the current year with the assumed inflation rate. Since the assumed depreciation period for all cases was 10 years, the annual capital cost was 10% of the total capital costs of the major equipment items, determined as described above. The cost per pound of hydrocarbon removed was then the total current year cost (the sum of the yearly costs) divided by the total pounds of hydrocarbon removed during the operating lifetime of the ISSV system.

With the above approach to the operating lifetime analysis, the unit processing cost for ISSV was dominated by the annual expense for all cases considered in this study. In fact, this would be true for all cases in which the depreciation period for the capital equipment was on the order of the time assumed here and the operating lifetime was equal to or less than the depreciation period (the

logic here for a depreciation period of 10 years was that the equipment could be used for other projects). If the operating lifetime and the depreciation period were always equal (which assumes a one-time use of the equipment), the capital costs would become more of a factor as shorter times were examined. Different scenarios such as these may be readily analyzed using the values for capital cost and operating expense that were calculated for the base year.

B. ENGINEERING DESIGN TRANSITION

Equilibrium removal assumptions, as described in the model of Appendix B, were used to provide the basis for this economic analysis. This equilibrium model was found to match the results from the Hill AFB demonstration quite well. Output of the model, using a weathered JP-4 contaminant composition and a soil temperature of 55°F, provided two correlation equations for the behavior of the ISSV system;

$$\log_{10}(Y) = 0.83235 - 0.02372\,(\log_{10}(X) + 2)\,, \tag{F-1}$$

for X $\leq$ 0.09 and

$$\log_{10}(Y) = -1.038 + 0.4878\,(\log_{10}(X) + 2) - 0.3325(\log_{10}(X) + 2)^2 + 0.02291\,(\log_{10}(X) + 2)^3\,. \tag{F-2}$$

for X > 0.09

where

X = cumulative air flow per initial spill, liters/gram, and

Y = current air-stream concentration, grams of contaminant/liter of air.

For the economic analyses, only the second of these two correlation equations is required. In all cases evaluated, X exceeds 0.09 very early in the initial time interval.

The equilibrium model also allowed the development of a correlation equation for the percent of the original spill remaining in the ground, as function of the same abscissa X as defined above.

$$\log_{10}(\textit{Percent remaining}) = 1.99599 - 0.002503\,(\log_{10}(X) + 2) + 0.005704\,(\log_{10}(X) + 2)^2 - 0.007015\,(\log_{10}(X) + 2)^3\,. \tag{F-3}$$

Since the equilibrium assumptions allow removal projections on a scale or normalized basis, these correlation equations may be used for the transition from engineering design, as discussed in other sections of this report, to the economic analyses presented in this section for any spill size and remediation time scale. The selected value for the cleanup parameter X and values for other physical

remediation time scale. The selected value for the removal factor X (referred to as "Target Cleanup Parameter" in spreadsheet VENT-2.100) and values for other physical parameters may be input into the spreadsheet, as indicated in Table F-1 (from Table 1 of VENT-2.100). All of the parameters in Table F-1 may be treated as input variables, except for those identified as derived variables. Those variables used parametrically for cost analyses are identified later. Tables F-2 and F-3 present information (from Tables 2 and 3 of VENT-2.100) concerning the progression of the cleanup as calculated from the data in Table F-1 using the above correlations.

The actual spills of interest generally will be JP-4 jet fuel, which is a complex mixture of chemical compounds and whose composition will shift with time as the spill cleanup progresses. In the *economic analysis*, this changing composition is of concern only in the case of emissions control with carbon adsorption. The method used to evaluate this case is discussed in more detail later.

The heat of combustion of the hydrocarbon contaminant is included in order to estimate the impact during cleanup on the total heat load of the catalytic oxidation unit. The catalyst bed might possibly be damaged by overheating caused by combustion of the contaminant itself. As shown later, however, the heating provided by combustion of the contaminant itself amounts to only about 7 percent of the total heating requirements during the very early stages of clean up, and that percentage declines quite rapidly as the air stream concentration declines. Thus, for purposes of economic evaluation, the heating contribution arising from the contaminant itself is ignored in all cost and expense estimating.

In Table F-1, the input parameters for the surrogate contaminant normally will not be changed. The input spill parameters are spill size, a range of 100 to 50,000 gallons having been evaluated for this document, and target cleanup time in number of quarters (1 quarter equals 3 months). A matrix of these two spill parameters is automatically generated when the spreadsheet is run. The extraction vacuum, the removal factor (target cleanup parameter), and the average carbon recycle interval (as a fraction of the total cleanup time) may be specified. The other parameters are either derived or in most cases would not be changed from the values shown.

For the purposes of economic assessment, a performance level of approximately 80 percent removal (or X=1000 liters/gram) was used as the basis of comparison (the reason for the selection of 80 percent removal is discussed in the main body of this document). All values listed as total costs or total costs per mass removed are calculated in terms of the time necessary to reach this level of treatment. The total cleanup time is handled in discrete time increments of one quarter of a calendar year, from one to twenty quarters, or up to a maximum of five years cleanup operation time. Given

TABLE F-1. OPERATING INPUT VARIABLES

EQUIVALENT CONTAMINANT INFORMATION (1)			
Equivalent Chemical Spill Species	[NAME] (2)	=	n-HEXANE
Equivalent Molecular Formula	[FOR]	=	C6H14
Equivalent Molecular Weight	[MW]	=	86.17
High Heat Of Combustion, Vapor, kJ/gmol	[HHC]	=	4194.80
Low Heat Of Combustion, Vapor, kJ/gmol	[LHC]	=	3886.73
Low Heat Of Combustion, Vapor, BTU/lb	[LH]	=	19407.94
SPILL PARAMETERS			
Initial Spill Size, gallons	[SP]	=	50000
DERIVED Initial spill size, liters	[LS]	=	189272
DERIVED Initial spill size, grams	[G]	=	1.247E+08
DERIVED Initial spill size, pounds	[LB]	=	2.750E+05
OTHER OPERATING PARAMETERS			
Target Cleanup Parameter, DePaoli	[X]	=	1000
Target Cleanup Time, Quarters	[QTR]	=	20
Carbon Recycle, Fraction of Cleanup Time	[RF]	=	0.1
Average Carbon Recycle Interval, Days	[RI]	=	155.125
Annual Operating Load Factor {For 365 days, LF = 1.00}	[LF]	=	0.85
DERIVED Target Cleanup Time, Days	[DMAX]	=	1551.25
DERIVED Target Cleanup Time, Minutes	[MINMAX]	=	2.234E+06
DERIVED Air Flow, liters/min	[AFL]	=	55838
DERIVED Air Flow, scfm	[AFF]	=	1972
Pumping Vacuum, Inches Water	[IW]	=	100
Pump/Fan Electric Efficiency	[PEF]	=	40
Other Motor Electric Efficiencies	[MEF]	=	85
Incinerator Fuel Efficiency	[FE]	=	85
Incinerator Percent Heat Recovery	[HR]	=	30

(1) The actual spill is a general type of jet fuel, i.e. JP-4. For calculation purposes here, n-Hexane is used as a surrogate. Refer to text discussion of this n-Hexane equivalent.

(2) [ ] is the initial location of a named variable.

TABLE F-2. QUARTERLY CLEANUP INFORMATION

CUMULATIVE TIME		CUMULATIVE AIR FLOW	METRIC UNITS		PERCENTAGE OF SPILL	
Periods + [PER]	Days + [D]	Standard Cubic Feet [SCF]	Abscissa liter/g [XT]	Ordinate g/liter [Y]	Remaining [RES]	Removed [GONE]
1	77.56	2.20E+08	50.0	0.00238	51.25	48.75
2	155.13	4.40E+08	100.0	0.00115	42.48	57.52
3	232.69	6.61E+08	150.0	0.00074	37.50	62.50
4	310.25	8.81E+08	200.0	0.00054	34.08	65.92
5	387.81	1.10E+09	250.0	0.00042	31.51	68.49
6	465.38	1.32E+09	300.0	0.00034	29.48	70.52
7	542.94	1.54E+09	350.0	0.00029	27.80	72.20
8	620.50	1.76E+09	400.0	0.00025	26.39	73.61
9	698.06	1.98E+09	450.0	0.00022	25.18	74.82
10	775.63	2.20E+09	500.0	0.00019	24.11	75.89
11	853.19	2.42E+09	550.0	0.00018	23.17	76.83
12	930.75	2.64E+09	600.0	0.00016	22.33	77.67
13	1008.31	2.86E+09	650.0	0.00015	21.57	78.43
14	1085.88	3.08E+09	700.0	0.00013	20.88	79.12
15	1163.44	3.30E+09	750.0	0.00012	20.25	79.75
16	1241.00	3.52E+09	800.0	0.00012	19.67	80.33
17	1318.56	3.74E+09	850.0	0.00011	19.14	80.86
18	1396.13	3.96E+09	900.0	0.00010	18.64	81.36
19	1473.69	4.18E+09	950.0	0.00009	18.18	81.82
20	1551.25	4.40E+09	1000.0	0.00009	17.75	82.25

TABLE F-3. QUARTERLY CLEANUP INFORMATION

CUMULATIVE TIME Periods + {PER}	CUMULATIVE TIME Days + {D}	PERCENTAGE OF SPILL Remaining {RES}	PERCENTAGE OF SPILL Removed {GONE}	OPERATING YEARS See Footnotes [OPY]	POUNDS REMOVED QUARTERLY [AR]
1	77.56	51.25	48.75	0.25	134068
2	155.13	42.48	57.52	0.50	24100
3	232.69	37.50	62.50	0.75	13698
4	310.25	34.08	65.92	1.00	9400
5	387.81	31.51	68.49	1.25	7061
6	465.38	29.48	70.52	1.50	5598
7	542.94	27.80	72.20	1.75	4603
8	620.50	26.39	73.61	2.00	3884
9	698.06	25.18	74.82	2.25	3343
10	775.63	24.11	75.89	2.50	2922
11	853.19	23.17	76.83	2.75	2586
12	930.75	22.33	77.67	3.00	2313
13	1008.31	21.57	78.43	3.25	2086
14	1085.88	20.88	79.12	3.50	1895
15	1163.44	20.25	79.75	3.75	1733
16	1241.00	19.67	80.33	4.00	1593
17	1318.56	19.14	80.86	4.25	1472
18	1396.13	18.64	81.36	4.50	1366
19	1473.69	18.18	81.82	4.75	1272
20	1551.25	17.75	82.25	5.00	1189

KEY INPUT PARAMETERS

Spill Gallons	{SP}	=	50000
Spill Pounds	{LB}	=	274983
Air Flow	{AFF}	=	1972
Load Factor	{LF}	=	0.85
Percentage of Spill Removed	{Max GONE}	=	82.25

\+ Time intervals are quarters of a calendar year, and time used for calculation purposes is adjusted for the specified load factor.

X=1000 liters/gram and a specified cleanup time in quarters (with actual operating time adjusted to the load factor of Table F-1), it is possible to calculate a required air-flow rate in standard ft^3/minute. That air-flow rate value is needed for subsequent cost estimating purposes, and the derived value is shown in Table F-1.

The variability of site properties and possible vent configurations makes correlation of flow rate and vacuum impossible for the general case. Therefore, vacuum requirement is handled as an input rather than a derived variable (correlation of vacuum and flow rate could be made for a specific site using the methods of Section IV or Section V.C.). The spread-sheet model assumes rotary-lobe positive-displacement blowers for generation of vacuum. These devices should cover a range up to approximately 200 inches H_2O. For applications requiring greater suction pressures to induce adequate flow, capital and operating cost correlations for other types of blowers would need to be substituted. Other design parameters found in Table F-1 are generally self-explanatory.

C. COST ESTIMATING

1. Financial Input Parameters

Table F-4 (from Table 4 of VENT-2.100) summarizes the financial input parameters used as part of the estimation of both fixed capital costs and annual expense (non-capital costs).

a. Inflation Rates

The Chemical Engineering and the Marshall & Swift indices are two of the most commonly used sets of inflation data for the chemical process industries. Both sets are published monthly in updated form in Chemical Engineering, which is the source of inflation data for this study. The compound average of the two inflation indices for the period 1977-89 is 4.84 percent annual inflation. That figure is used in all cases where cost data from the technical literature must be updated to 1990 costs.

Since future inflation data are non-existent, that same annual inflation rate is projected forward over the operating lifetime evaluated in this study. The rate is, of course, an input variable and the spreadsheet is set up to allow evaluation of the cost impact of upward of downward variations in the inflation rate.

TABLE F-4. FINANCIAL INPUT PARAMETERS[a]

PARAMETER	VALUE
Annual Inflation Rate [INF]	0.0484
Annual Real Interest Rate [RIR]	0.0500
Annual Applied Interest Rate [INT]	0.0984
DERIVED Quarterly Interest Rate [QINT]	0.0237
Electricity Costs, 1990 $/kwh [EC]	0.06
Fuel Oil Costs, 1990 $/MMBTU [FC]	10.00
Overhead Rate, Pump System [OR1]	0.85
Overhead Rate, Air Treatment System [OR2]	0.25
Equipment Installation Factor, Pump [EF1]	1.40
Equipment Installation Factor, Other [EF2]	1.80

[a]Refer to accompanying text for full discussion of all financial parameters. All of the parameters in this table are input variables except for those labeled as DERIVED values.

b. Interest Rates

The interest rates applied in this study are related to the projected inflation rate using the concept of the real interest rate. The applied interest rate is the sum of the inflation rate and the real interest rate, thus providing a realistic linkage between the two values. In recent years, the real interest rate has fluctuated around 5 percent annually. The use of this real rate is consistent with the current state of the national economy and with recent practices in studies done for the U.S. GAO (References 51-54).

For the purpose of these economic evaluations, elapsed time intervals of 0.25 calendar year were specified. Thus, for subsequent operating lifetime analyses a quarterly rate was derived as

$$QINT = (1 + INT)^{0.25} - 1 \quad . \qquad \text{(F-4)}$$

c. Energy Costs

Electricity and No. 2 oil cost figures are typical of those now being charged nationally. However, there are regional variations, as well as variations related to contract terms.

d. Overhead Rates

The overhead rates shown in Table F-4 are applied to a cost base equal to the total annual expense (non capital costs), exclusive of interest on debt. The higher of these two rates (OR1) is applied only to the pump system expenses, since all of the labor costs are loaded onto that unit operation as the one operation common to all three operating alternatives. The lower of the two rates (OR2) is applied to the expense base for both of the air treatment systems, except that in the case of carbon adsorption treatment the very high cost component for carbon regeneration is excluded from the overhead base.

Some sources (References 55 and 56) calculate overhead as a collection of rates applied to several bases. Numerically, that same result can be generated by using a single rate applied to a single base. In the recently completed economic analysis of VOC groundwater cleanup operations (Reference 57), both methods were used and compared. That analytical comparison documented the validity of the simpler single rate and single base approach, which is used in the current study.

e. Equipment Installation Factors

The equipment installation factor for pumps and fans is taken from Walas (Reference 58). Neveril (Reference 56) specifies an equipment installation factor of about 1.6 for the other two unit operations, exclusive of site preparation. That factor was adjusted upward slightly to 1.8 to allow for a moderate amount of site preparation costs.

2. Vacuum Blower

The vacuum blower is common to all three operating alternatives considered in this study. Cost estimating is based upon the use of a rotary-lobe positive-displacement pump, as used in recent field studies discussed elsewhere in this report. The pumps selected are capable of generating a vacuum head up to about 15 inches Hg or about 200 inches H_2O. Capital costs in thousands of 1990 dollars are based upon actual cost data for two such pumps, rate at 250 and 1000 std ft^3/minute, inclusive of control units. The actual cost data were derived from the Hill AFB demonstration.

The normal practice (Reference 55) of using log-log analysis of cost vs capacity was used to generate the following capital cost estimating correlation, in 1990 dollars;

$$COST = 8.984\ (AFF/1000)^{0.2637}\ , \qquad \text{(F-5)}$$

where AFF is the derived air flow rate in standard cubic feet per minute.

The equipment installation factor, previously discussed in relation to Table F-4, is used to adjust the estimate to an installed value.

Electrical power requirements were calculated from the previous information on air flow rate, vacuum head, and overall pump electrical efficiency as found in Table F-1. The power use is adjusted for the load factor as also found in Table F-1.

Annual maintenance costs vary substantially, depending upon the particular kind of equipment system, location, use conditions, etc. For ratio estimating, as used here, annual maintenance costs equal to 5 to 10 percent of the fixed capital costs are often found in the technical literature (References 55 and 56). As a consciously conservative approach, the upper value range of maintenance percentage rates is used for the venting only case and the venting plus catalytic oxidation case. For the case of venting with carbon adsorption as the emissions control option, annual maintenance costs were calculated as 1 percent of the fixed capital costs. Because of the relatively high capital costs for this case, unrealistically high maintenance costs would results using the 10 percent factor.

Direct labor is estimated on the basis of 0.25 man-day per day, or 0.25 FTE (full time equivalent), at an annual 1990 salary level of $24,000. This is consistent with a range of values given by Neveril (Reference 56). The approach to estimation of overhead costs has already been discussed in relation to the financial inputs of Table F-4. Table F-5 (from Table 5 of VENT-2.100) shows the capital cost and annual operating expense for a rotary lobe blower. These costs were based on the inputs presented in Tables F-1 and F-4.

TABLE F-5. ROTARY LOBE POSITIVE DISPLACEMENT PUMP (THOUSANDS OF 1990 DOLLARS)

AIR PUMPING SYSTEM

Fixed Capital Costs, thousands of 1990 $	[F1]	=	10.746
Installed Cap Costs, thousands of 1990 $	[FC1]	=	15.044

For Annual Interest on Capital Debt See Lifetime Analysis

ANNUAL EXPENSE

Fan Power Requirement, kW	[KW1]	=	69.316
Annual Power Use, kWh [Adjusted for load factor, LF]	[KWH1]	=	5.161E+05
Annual Electricity Costs	[EL1]	=	30.968
Maintenance @ 10% of FC1	[M1]	=	1.504
Direct Labor, 0.25 FTE @ $24k/y	[L1]	=	6.000
Total Direct Annual Expense	[DE1]	=	38.472
Overhead on Annual Direct Expense	[OH1]	=	32.701
TOTAL ANNUAL EXPENSE	[EXP1]	=	71.173

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(1) Capital cost correlation equation is based upon actual cost data for rotary lobe positive displacement pumps, provided by DePaoli of ORNL.

Inputs from Table F-1 are used in the fixed capital and the annual expense calculations above. Refer to accompanying text for more details.

3. Catalytic Oxidation Unit

Fixed capital costs in thousands of 1977 dollars are estimated from sizing information from preceding tables, and from cost correlations of Vatavuk and Neveril (Reference 59). The latter provides a non-linear cost correlation for air flow rates over a range much larger than needed for this study. In the lower flow rate range of 0-10,000 std ft^3/minute, their cost correlation can be approximated closely by the following linear relationship, which is used in the present study.

$$COST = 2\ AFF/1000 + 70 \tag{D-6}$$

where the cost is in thousands of 1977 dollars and AFF is the air flow rate in std ft^3/minute.

As a conservative estimate, the catalyst cost is listed as an expense on the assumption of annual replacement. After inflating to 1990 dollars, the equipment installation factor, as discussed in relation to Table F-4, is used to derive the catalytic oxidation unit installed cost.

The air stream is assumed to be preheated to an operating temperature of 1,000°F by combustion of Number 2 fuel oil. This corresponds to the situation where the hydrocarbon concentration is so low that the heat of combustion does not produce a temperature rise. The heating requirements are calculated using the mean heat capacity of air in the range 70 to 1500°F (Reference 60), the air flow rate, and the input values of Table F-1 for the load factor, the overall thermal efficiency of the unit, and a 30 percent heat recovery factor.

In the very early stages of the combustible material cleanup, the contaminant concentration in the air stream may be sufficient to contribute significantly to the temperature rise in the catalyst bed and could cause catalyst damage by overheating. Also, during these early stages, the contaminant concentration in the air stream may be sufficient to supply about 7 percent of the total heat requirement. For all cases considered, however, that percentage declines very rapidly as the air stream concentration declines. Thus, for the economics portion of this study, the contribution from the contaminant itself to the heating requirement is ignored.

Annual electrical costs are calculated on the basis of the required air flow rate, the specified electrical efficiency from Table F-1, and an overall pressure drop of 10 inches of H_2O. Typical pressure drops for many kinds of fiber structure industrial filters are 3 to 4 inches of H_2O. Maintenance costs are estimated on the same basis as previously discussed for the pump system.

The assumptions involved in the calculation of the overhead were discussed in connection with Table F-4.

Table F-6 (from Table 6 of VENT-2.100) presents the capital cost and annual operating expense for a catalytic oxidation unit. These costs were based on the inputs from Tables F-1 and F-4.

4. Carbon Adsorption Units

The gas stream from a soil vapor extraction process will range from initially very high to quite low concentration near the end of the operation. Thus, carbon usage rate would be expected to vary greatly during the course of an operation. Such variation is not accounted for in this manual. Rather, an average recycle interval is used. The recycle interval is simply the time between regenerations of the carbon bed. To provide a bed size for an entire operation, a value for the carbon recycle interval is input into Table 1 of VENT-2.100. The value is input as a fraction of the total cleanup time. Thus, if a value of 0.1 is used, the carbon bed would be regenerated 10 times during the cleanup time. The size of the carbon bed is calculated based on the average amount of contaminant removed during a recycle interval and the average carbon loading capacity. For actual field implementation, only certain common bed sizes would be available. Carbon regeneration costs were used in the analysis rather than including disposable carbon. The costs of the latter would be expected to be at least as much as for regeneration in most cases and, furthermore, would involve transport and disposal of the loaded carbon.

Actual spills of interest will generally be complex mixtures of compounds. Thus, not only the concentration, but also the composition of the contaminants in the gas stream will shift with time as spill cleanup by ISSV progresses. A complex routine for calculation of carbon consumption in terms of contaminant concentration and composition has not been developed in the spreadsheet at this time. However, a value for the average carbon loading capacity was estimated based on the predictions of the equilibrium removal model for the weathered JP-4 fuel composition and the Freundlich equation (Reference 61). Using the equilibrium model, the composition and concentration of the contaminants in the extracted gas stream was calculated as a function of the percent removal of the spill. Using the Freundlich equation, the carbon requirement was also estimated as a function of the percent removal. An average carbon loading capacity was then calculated from these results. The value used in the spreadsheet calculations for this manual was 0.25 grams contaminant/gram carbon. This is lower than the value calculated using the Freundlich equation. The intent was to use a value that may be more representative of a regenerated carbon than a fresh carbon. The value for carbon loading capacity may be varied in the spreadsheet to see the effect on carbon off-gas treatment costs.

TABLE F-6. CATALYTIC OXIDATION COST ESTIMATES (THOUSANDS OF 1990 DOLLARS)

FIXED CAPITAL COSTS			
Fixed Capital Costs, thousands of 1990 $	[IF2]	=	86.80
Installed Cap Costs, thousands of 1990 $	[FC2]	=	156.25
AIR STREAM HEATING DATA			
Air Heating Requirements, MMBTU/yr (1)	[H2]	=	15527.4
Adjusted, MMBTU/yr (2)	[AH2]	=	12787.2
ANNUAL EXPENSE			
Fan Power Requirement, kW	[KW2]	=	2.727
Annual Power Use, kWh [Adjusted for load factor, LF]	[KWH2]	=	2.031E+04
Annual Fuel Costs	[AF2]	=	127.872
Annual Electricity Costs	[EL2]	=	1.218
Maintenance @ 10% of FC2	[M2]	=	15.625
Catalyst Cost [Annual Replacement]	[CAT]	=	2.598
Total Direct Annual Expense	[DE2]	=	147.313
Overhead on Annual Direct Expense	[OH2]	=	36.828
TOTAL ANNUAL EXPENSE	[EXP2]	=	184.142

Cost estimates above are in thousands of 1990 $, and are based upon inputs shown in the preceding Table 1. Also see text.

(1) Based upon the heat capacity of air at standard conditions.
(2) Adjusted for thermal efficiency of incinerator, and the stated percentage heat recovery.
(3) Maximum heat available from combustion of the contaminant. Declines annually, so is ignored in economic analysis.

Annual debt interest is handled via operating lifetime analysis.

As mentioned above, because of the wide range of contaminant concentration experienced during soil venting, the carbon loading rate would also be expected to vary significantly. The variation in carbon loading rate is due not only to the variation of the rate of hydrocarbon extraction from the soil (equal to the air flow rate times the hydrocarbon concentration), but also to the dependence of carbon capacity on the hydrocarbon concentration in the air stream. In the case of a single contaminant species such as, for example, trichloroethylene or benzene, the carbon capacity decreases with concentration in the air stream. Thus, while the decreasing concentration during the course of extraction would lengthen the carbon recycle interval, the decreasing carbon capacity would tend to shorten the interval. These opposing effects would tend to reduce variation of the recycle interval during the extraction process. However, for the assumed weathered JP-4 fuel composition, as the air stream contaminant concentration decreases with time, the composition of the air stream shifts toward heavier and heavier (i.e., higher molecular weight) carbon compounds. Consequently, the carbon capacity does not change significantly as concentration decreases, because these heavier compounds adsorb more strongly on the carbon. Thus, the carbon recycle interval would be expected to be inversely related to the hydrocarbon concentration.

Vatavuk and Neveril (Reference 62) provide a non-linear correlation equation and a graph for carbon adsorption cost estimating. For this study, the graph was linearized and simplified to produce an expression for estimating cost. Thus, the fixed capital cost for the carbon adsorption unit, inclusive of all hardware but exclusive of the initial carbon load, was calculated as

$$COST = 3.32\ CAP + 36.4\ , \tag{F-7}$$

where COST is in thousands of 1982 dollars, and CAP is unit size as thousands of pounds of carbon.

The cost (expense) in 1988 dollars for carbon regeneration is estimated from the following correlation (Reference 63):

$$COST = 0.77 - 1.94\ (GAC/10) + 2.81\ (GAC/10)^2 - (GAC/10)^3\ . \tag{F-8}$$

This expression results from curve fitting the multihearth regeneration cost curve of Figure 3 of the reference. The cost is in dollars per pound of carbon regenerated, and GAC is the amount of carbon (millions of pounds) regenerated per year. The cost estimate allows for 25 percent excess capacity, about 12 percent carbon replacement during each regeneration, and for all other related costs. In both cases, the costs are inflated to 1990 dollars.

The cost estimates for air treatment by carbon adsorption are summarized in Table F-7 (from Table 7 of VENT-2.100). Again, the costs are based on the inputs in Tables F-1 and F-4. It should be noted that the cost of carbon regeneration, which is a large component of the annual expense, has been excluded from the base for overhead. Otherwise, the overhead would be somewhat artificially driven upward.

D. SUMMARY OF COST DATA

Tables F-8, F-9, and F-10 (from Tables 8, 9, and 10 of VENT-2.100) summarize the total fixed capital cost and the quarterly expense cost for each of the three configurations described earlier. Note that these costs are for the initial or base year, and that the expense cost is on a quarterly rather than annual basis. For example, Tables F-5, F-6, and F-7 correspond to the case of a 50,000 gallon spill and a cleanup time of 20 quarters. For venting only in Table F-5, the installed capital cost and the annual expense are seen to be $15,044 and $71,173, respectively. Thus, in the summary for venting only in Table F-8, the entries in the last row and last column show (in thousands of dollars) the capital cost as 15.044 and the quarterly expense as 17.793. Note that the 17.793 was simply derived by dividing the annual expense from Table F-5 by 4 and expressing the result in thousands of dollars. The data in Table F-9 represent a combination of the information from Tables F-5 and F-6, and the data in Table F-10 a combination of the information from Tables F-5 and F-7. These data cover all 35 elements of the data matrix—for spill sizes from 100 to 50,000 gallons and for cleanup times from 1 to 20 calendar quarters. These data are generated from the inputs as found in the earlier illustrative tables of the spreadsheet. Note that Tables F-5, F-6, and F-7 correspond to only one of these 35 data sets. Each of these tables is calculated 35 times when VOC-2.100 is run per the instructions in Appendix G. However, after all calculations have been completed, only the information for the last of the 35 data sets is displayed in Tables F-5, F-6, and F-7.

Table F-11 shows the air flow rate for each combination of spill size and clean-up period. Note that the upper right corner of Tables F-8, F-9, and F-10 involves air flow rates lower than about 100 std ft^3/minute, and the lower left corner involves air flow rates higher than about 5,000 std ft^3/minute. Although ISSV systems typically would not be expected to be designed for such flow rates, the cost figures are included for completeness of the data matrix.

E. OPERATING LIFETIME FINANCIAL ANALYSIS

The operating lifetime analysis for each of the 35 data sets from VENT-2.100 is performed with spreadsheet VENT-2.300. As discussed in Appendix G, the primary inputs for each case are the total capital cost, the yearly operating expense cost (4 times the quarterly expense cost from VENT-2.100), the number of quarters, and the mass of contaminant removal from the soil.

TABLE F-7. CARBON ADSORPTION COST ESTIMATES (THOUSANDS OF 1990 DOLLARS)

CARBON SYSTEM DESIGN SUMMARY

Initial Spill Size, Pounds	{LB}	=	274983
TOTAL LIFETIME Spill Cleanup, lbs	[CL1]	=	226183
Average Carbon Recycle Interval, Days	{RI}	=	155.125
Average Cleanup per Recycle Interval, lbs	[CL2]	=	22618.33
Average Stream Loading, gm/liter	[ASL]	=	0.00230
Average Lifetime Carbon Loading, lb/lb [SEE TEXT DISCUSSION]	[CL]	=	0.2500
CARBON REQUIREMENT for Stated Interval, lbs [Safety Margin = 20%. This is the design size for the carbon unit. ONLY ONE UNIT IS INSTALLED	[CAR]	=	108568
Quarterly Carbon Use, lbs	[QCR3]	=	54284
Annual Carbon Use, millions of lbs	[ACR3]	=	0.217
Air Heating Requirements, MMBTU/yr (1)	[H3]	=	415.3
Fan Power Requirement, kW	[KW3]	=	2.727
Annual Power Use, kWh [Adjusted for load factor, LF]	[KWH3]	=	2.031E+04

FIXED CAPITAL COSTS

Fixed Capital Costs, thousands of 1977 $	[F3]	=	396.85
Fixed Capital Costs, thousands of 1990 $	[IF3]	=	733.62
Installed Cap Costs, thousands of 1990 $	[FC3]	=	1701.86

ANNUAL EXPENSE

Initial [*One Time*] *Carbon Purchase*	[CP3]	=	190.67
Carbon Recycle Cost, 1990 $/lb	[CR3]	=	0.801
Carbon Recycle Costs	[CRT3]	=	174.030
Annual Fuel Costs	[AF3]	=	4.153
Annual Electricity Costs	[EL3]	=	1.218
Maintenance @ 1% of FC3	[M3]	=	17.019
Total Direct Annual Expense	[DE3]	=	196.420
Overhead on Annual Direct Expense	[OH3]	=	49.105
TOTAL ANNUAL EXPENSE	[EXP3]	=	245.525

(1) Based upon the heat capacity of air at standard conditions.

THIS TABLE MAKES USE OF A NUMBER OF SIMPLIFIED DESIGN ASSUMPTIONS FOR BEHAVIOR OF THE CARBON ADSORPTION UNITS, AND THESE ARE DISCUSSED IN DETAIL IN THE ACCOMPANYING TEXT.

TABLE F-8. CAPITAL AND QUARTERLY EXPENSE SUMMARIES (VENTING ONLY) (THOUSANDS OF 1990 DOLLARS)

SPILL SIZE*	ITEM**	QUARTERS ELAPSED TIME 1	2	4	10	20
100	[FC1]	6.437	5.361	4.466	3.507	2.921
452	[EXP1]	3.646	3.309	3.125	2.994	2.939
500	[FC1]	9.841	8.197	6.827	5.361	4.466
2262	[EXP1]	6.095	4.586	3.807	3.309	3.125
1000	[FC1]	11.815	9.841	8.197	6.437	5.361
4524	[EXP1]	9.050	6.095	4.586	3.646	3.309
5000	[FC1]	18.062	15.044	12.531	9.841	8.197
22620	[EXP1]	32.255	17.793	10.516	6.095	4.586
10000	[FC1]	21.685	18.062	15.044	11.815	9.841
45239	[EXP1]	61.068	32.255	17.793	9.050	6.095
25000	[FC1]	27.613	22.999	19.157	15.044	12.531
113099	[EXP1]	147.277	75.451	39.467	17.793	10.516
50000	[FC1]	33.152	27.613	22.999	18.062	15.044
226197	[EXP1]	290.759	147.277	75.451	32.255	17.793

*The first number in each group, i.e., 100 up to 50000, is the total spill size in gallons. The second number, i.e., 452 up to 226197, is the number of pounds of spill cleaned up during the operation.

**FC refers to capital costs and EXP refers to operating expense costs. The operating expense costs have been adjusted to a quarterly basis.

TABLE F-9. CAPITAL AND QUARTERLY EXPENSE SUMMARY (VENTING PLUS CATALYTIC OXIDATION) (THOUSANDS OF 1990 DOLLARS)

SPILL SIZE*	ITEM**	QUARTERS ELAPSED TIME				
		1	2	4	10	20
100	[FC1 + FC2]	66.504	54.370	44.487	34.168	28.012
452	[EXP1 + EXP2]	7.254	5.725	4.830	4.144	3.823
500	[FC1 + FC2]	106.504	86.907	70.973	54.370	44.487
2262	[EXP1 + EXP2]	17.493	11.284	7.963	5.725	4.830
1000	[FC1 + FC2]	130.623	106.504	86.907	66.504	54.370
4524	[EXP1 + EXP2]	29.368	17.493	11.284	7.254	5.725
5000	[FC1 + FC2]	210.459	171.292	139.519	106.504	86.907
22620	[EXP1 + EXP2]	120.180	63.829	35.190	17.493	11.284
10000	[FC1 + FC2]	258.775	210.459	171.292	130.623	106.504
45239	[EXP1 + EXP2]	231.706	120.180	63.829	29.368	17.493
25000	[FC1 + FC2]	340.449	276.620	224.920	171.292	139.519
113099	[EXP1 + EXP2]	563.694	287.214	148.156	63.829	35.190
50000	[FC1 + FC2]	419.301	340.449	276.620	210.459	171.292
226197	[EXP1 + EXP2]	1114.542	563.694	287.214	120.180	63.829

*The first number in each group, i.e., 100 up to 50000, is the total spill size in gallons. The second number, i.e., 452 up to 226197, is the number of pounds of spill cleaned up during the operation.

**FC refers to capital costs and EXP refers to operating expense costs. The operating expense costs have been adjusted to a quarterly basis.

TABLE F-10. CAPITAL AND QUARTERLY EXPENSE SUMMARIES (VENTING PLUS CARBON ADSORPTION) (THOUSANDS OF 1990 DOLLARS)

SPILL SIZE*	ITEM**	QUARTERS ELAPSED TIME 1	2	4	10	20
100	[FC1 + FC3]	130.722	129.646	128.751	127.792	127.206
452	[EXP1 + EXP3]	6.394	4.879	4.104	3.619	3.445
500	[FC1 + FC3]	146.774	145.130	143.761	142.295	141.400
2262	[EXP1 + EXP3]	18.222	10.895	7.183	4.919	4.144
1000	[FC1 + FC3]	164.560	162.586	160.942	159.182	158.107
4524	[EXP1 + EXP3]	32.680	18.271	10.944	6.483	4.968
5000	[FC1 + FC3]	297.297	294.279	291.766	289.076	287.432
22620	[EXP1 + EXP3]	139.572	74.742	40.176	18.667	11.340
10000	[FC1 + FC3]	459.033	455.410	452.392	449.163	447.189
45239	[EXP1 + EXP3]	254.686	140.066	75.236	33.569	19.161
25000	[FC1 + FC3]	939.299	934.686	930.843	926.730	924.217
113099	[EXP1 + EXP3]	515.347	307.026	171.978	76.718	42.152
50000	[FC1 + FC3]	1735.401	1729.862	1725.249	1720.312	1717.294
226197	[EXP1 + EXP3]	843.507	517.818	309.496	144.019	79.189

*The first number in each group, i.e., 100 up to 50000, is the total spill size in gallons. The second number, i.e., 452 up to 226197, is the number of pounds of spill cleaned up during the operation.

**FC refers to capital costs and EXP refers to operating expense costs. The operating expense costs have been adjusted to a quarterly basis.

TABLE F-11. DEFINITION OF DATA SETS[a]

SPILL SIZE (gallons)	TIME QUARTERS (MONTHS)				
	3	6	12	30	60
100	79	39	20	8	4
500	394	19	99	39	20
1000	789	394	197	79	39
5000	3944	1972	986	394	197
10000	7888	3944	1972	789	384
25000	19710	9859	4930	1972	986
50000	39438	19719	9859	3944	1972

[a]Values in the above matrix are air flow rates, in standard cubic feet per minute.

1. Input Parameters

Interest and inflation rates are the same as those used earlier, except that the annual rates have been adjusted to quarterly rates. The standard time interval for the operating lifetime analyses is one calendar quarter, adjusted for the stipulated load factor.

All capital equipment is fully depreciated in a linear manner over a 10-year lifetime, with zero salvage. This is consistent with a median range of depreciation lifetimes reported elsewhere (Reference 55). The actual cleanup periods involved here do not, however, exceed five years. Thus, in each of these cases, the quarterly depreciation cost is equated to that derived from a 10-year schedule, which will lead to some residual salvage at the end of the clean up period.

Physical operating conditions are the matrix of initial spill sizes and of cleanup times, as shown in Tables F-8, F-9, and F-10.

2. Results

Tables 8, 9, and 10 in the main body of this document summarize the operating lifetime costs per pound of contaminant cleaned up for each of the three operating systems described earlier. The costs are in current year dollars, over the specified operating lifetime, beginning in 1990. Each table shows data for the 35 elements of the matrix of operating conditions, i.e., initial spill sizes from 100 to 50,000 gallons, and cleanup lifetimes from one to 20 calendar quarters (5 years maximum). For additional information, the tables show the individual contributions from fixed capital and expense costs. This information is included in order to illustrate a common operating situation in which the expense cost tends to dominate the total cost. The total cost numbers from Tables 8, 9, and 10 are presented graphically in Figures F-1 through F-3. The costs presented are for planning and estimation purposes and will require modification based on actual site conditions and final system design.

Comparison of different system designs becomes difficult without application to a particular site. For instance, the cost data presented in these tables and figures were developed with the assumption of a constant vacuum condition for the soil venting. In actuality, vacuum requirements may change significantly with flow rate. For increasing flow rate, more vents would be required to maintain vacuum levels. This additional cost for more vents, although likely to be comparatively small in most cases, is not considered in this analysis.

In conclusion, a powerful spreadsheet model for estimation of ISSV process costs has been developed. This model is particularly valuable for guidance in system design strategy and scheduling. It is likely more economical to perform ISSV in the shortest practical period, within equipment constraints such as vacuum requirements, number of vents, and piping size.

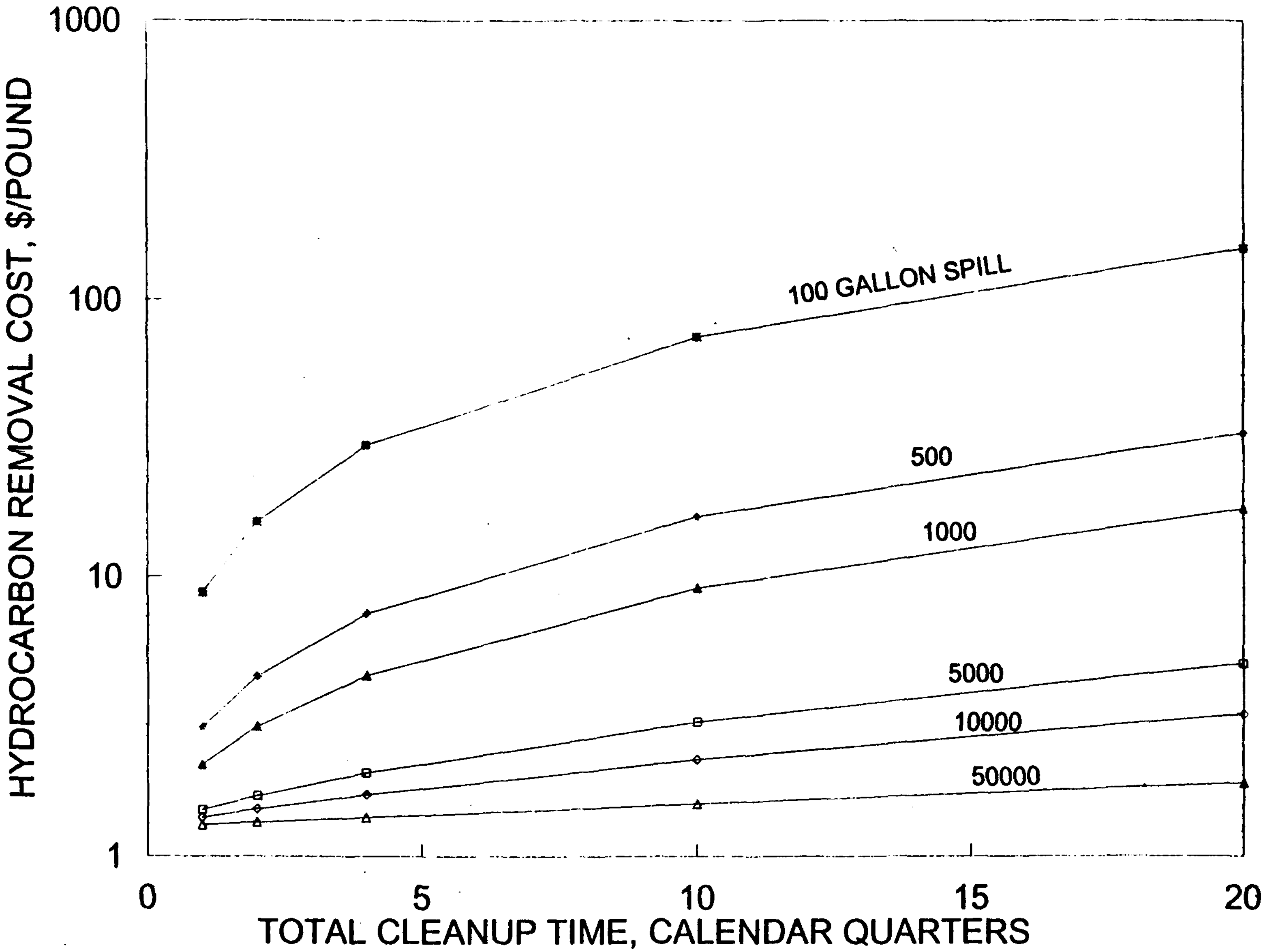

Figure F-1. Soil Venting Only - Variation of Hydrocarbon Removal Cost with Total Cleanup Time and Size of Jet Fuel Spill at 100 inches of Water; Constant Vacuum.

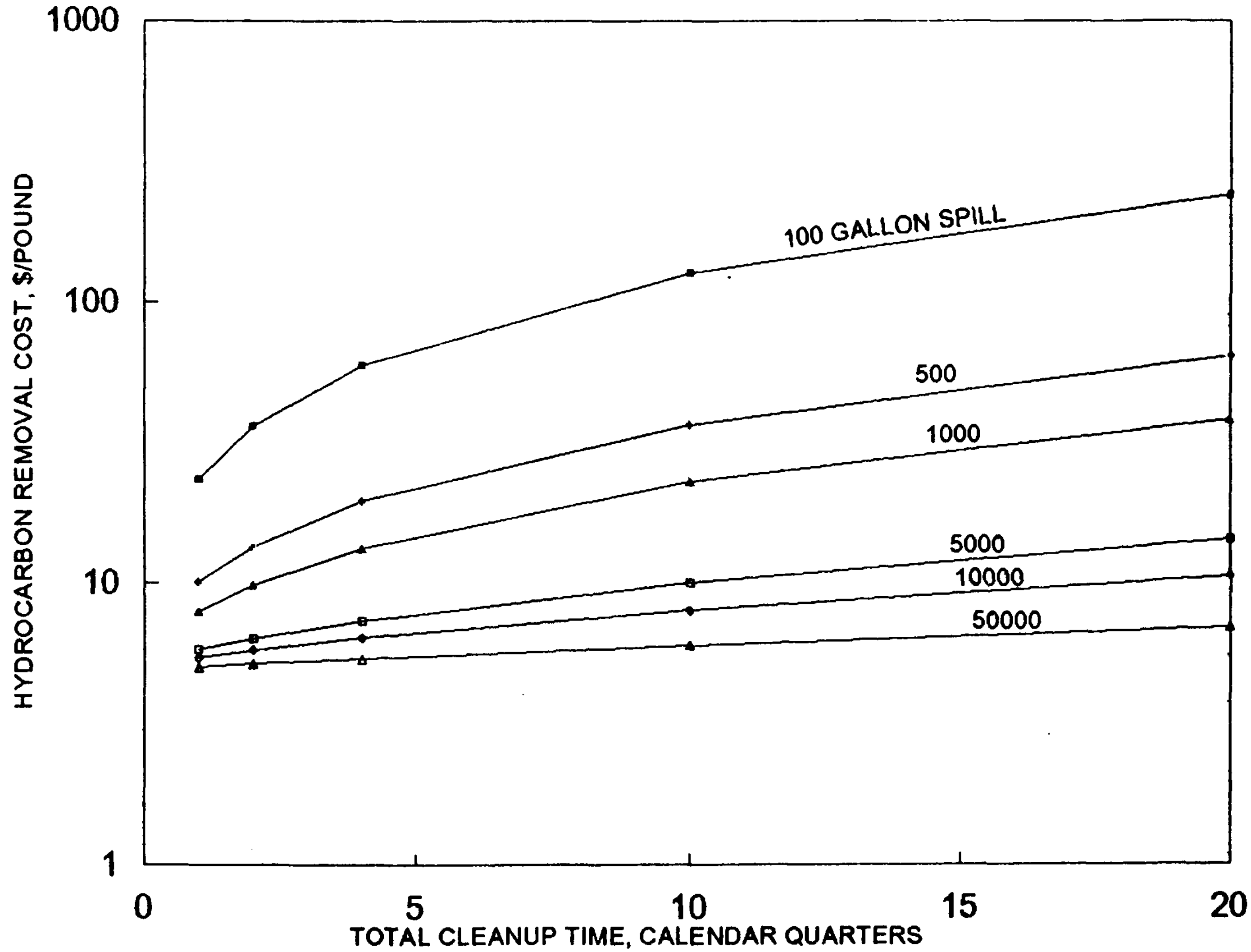

Figure F-2. Soil Venting with Catalytic Oxidation - Variation of Hydrocarbon Removal Cost with Total Cleanup Time and Size of Jet Fuel Spill at 100 inches of Water; Constant Vacuum.

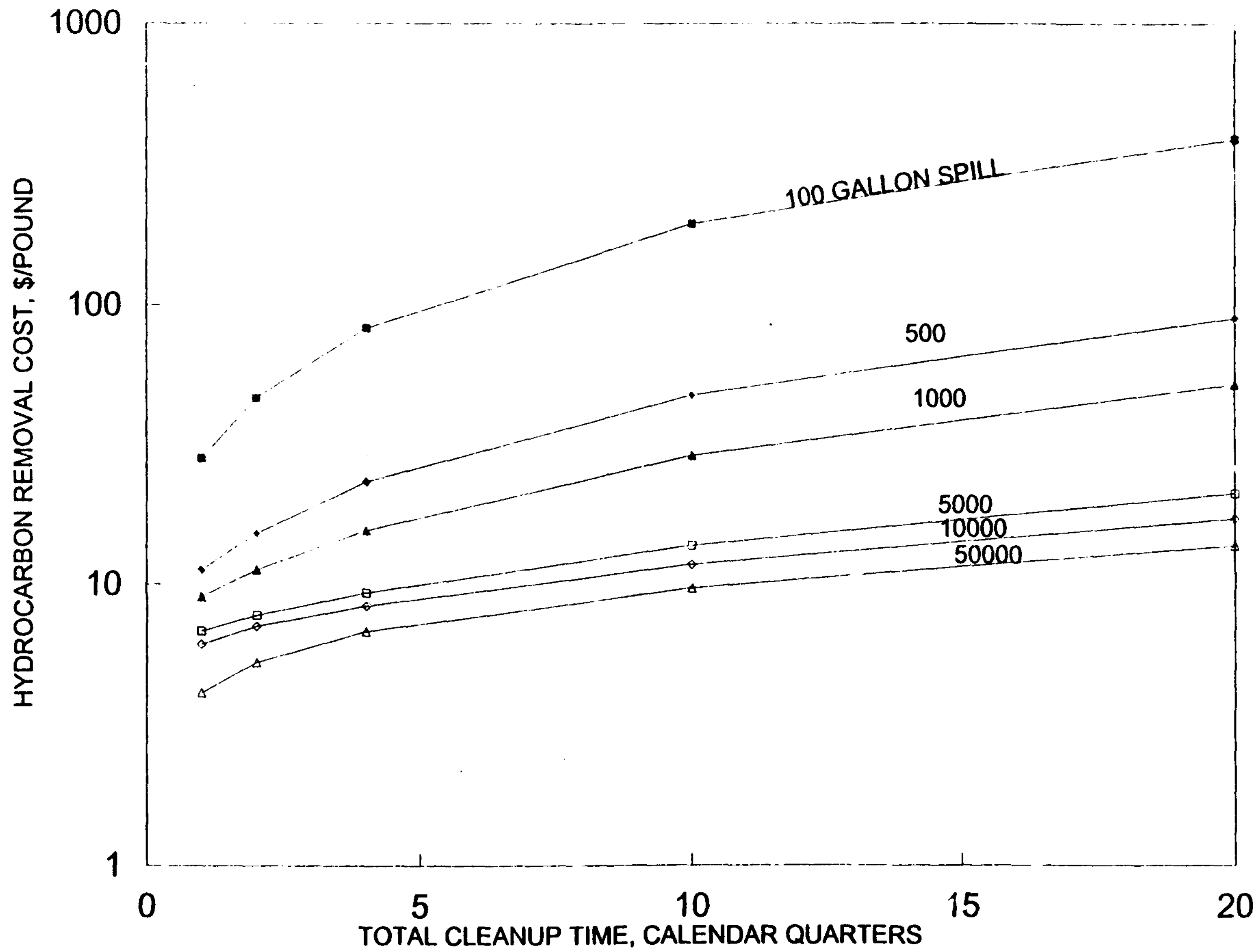

Figure F-3. Soil Venting with Carbon Adsorption - Variation of Hydrocarbon Removal Cost with Total Cleanup Time and Size of Jet Fuel Spill at 100 inches of Water; Constant Vacuum.

APPENDIX G

GUIDE TO USING SPREADSHEET FOR COST ESTIMATING PURPOSES

The following instructions assume that the appropriate spreadsheet has been loaded into MS Multiplan using the **TRANSFER LOAD** sequence. In the instructions, brackets, [ ], are used to indicate the name of a variable. When entering a variable name into a spreadsheet, do NOT enter the brackets. Instructions for running the spreadsheets VENT-2.100 and VENT-2.300 are given in this appendix. These spreadsheets constitute the ISSV econometric model that was described in detail in Section VII and Appendix F.

A. CALCULATION OF TOTAL CAPITAL AND QUARTERLY EXPENSE COSTS

The spreadsheet VENT-2.100 is used to determine the total fixed capital and quarterly expense costs (for the initial or base year) for ISSV at 35 different combinations of spill size and cleanup time. In the spreadsheet, notes and comments are included on the tables to help understand each table.

All physical inputs are handled in Table 1 of VENT-2.100. Also, several derived variables are included in Table 1. The input variables for the information on the equivalent contaminant usually would not be changed. This information is primarily used to calculate the contribution of the heat of combustion to the catalytic oxidation heating requirements. As noted, the spill size and the cleanup time parameters are not to be changed. The matrix of these parameters is run automatically by executing the macro GO, as discussed later. Other primary input parameters are cleanup parameter, the carbon recycle interval (expressed as fraction of total cleanup time), and pumping vacuum. The remaining input variables would usually not be changed.

All financial inputs are handled in Table 4 of VENT-2.100. These inputs include inflation and interest rates, electricity and fuel oil costs, overhead rates, and equipment installation factors. Input variables that are likely to be changed are the electricity and fuel oil costs.

Before making any changes to the inputs, one should temporarily suppress recalculations, while making sure that ITERATION is set to YES:

OPTIONS	RECALC	NO	ITERATION	YES

Input the desired values of the variables into Tables 1 and 4 of VENT-2.100. To locate any desired input variable (or any named variable, range, or area anywhere in the spreadsheet) in Table 1 or 4, use the GOTO NAME sequence. For example,

GOTO	NAME	[IW]	100

will locate the variable [IW] (the well vacuum) and set [IW] to 100 inches of water. After entering values for the variables of interest in Tables 1 and 4, run the macro GO by typing GO while holding down the ALT key.

The spreadsheet will now calculate the total fixed capital and quarterly expense costs for the matrix of spill size and cleanup time. On the IBM XT, the run time is approximately 30 minutes. On a 486 computer, the run time is about 45 seconds. The results of the calculations are output to Tables 8, 9, and 10 of VENT-2.100. To prepare print files for use with SIDEWAYS, etc., run the macro PF by typing PF while holding down the ALT key.

Tables 8, 9, and 10 of VENT-2.100 give the total capital and quarterly expense costs for the three cases of soil venting only, soil venting with catalytic oxidation, and soil venting with carbon adsorption, respectively. For each of the three cases, the costs are given for the 35 combinations of spill size and cleanup time. Each of the 105 sets of total capital and quarterly expense costs are then used as inputs to VENT-2.300, the lifetime financial analysis spreadsheet, to calculate the cost per pound of contaminant removed by ISSV.

B. LIFETIME FINANCIAL ANALYSIS

The spreadsheet VENT-2.300 is used to perform the lifetime financial analysis to determine the cost per pound of contaminant removed by ISSV. Notes and comments are included on the tables to help understand each table.

The set of input parameters needed for each lifetime financial analysis includes (1) the total capital cost, (2) the base year annual expense cost, (3) the number of quarters required for cleanup, and (4) the total pounds of contaminant removed during the cleanup. All four parameters belong to one of the 105 sets of capital and quarterly expense costs generated by VENT-2.100.

The spreadsheet may be run by the following steps.

1. As in Section A, suppress recalculations by:

OPTIONS	RECALC	NO	ITERATION	YES

2. In Table A of VENT-2.300, input the values for initial fixed capital [F] and initial annual expense [E] (Note that the values must be in thousands of dollars if the value for currency units is set to 1.0E+03. Note also that the expense is the <u>annual</u> expense, which is <u>four times</u> the quarterly expense from VENT-2.100). The other parameters in the table usually would not be changed. Again, as in Section A, use the GOTO NAME sequence to locate the variables.
3. In Table D of VENT-2.300, input the values for the lifetime cleanup in pounds [CLN] and the number of operating quarters [M] using the GOTO NAME sequence.
4. Initiate calculations by:

OPTIONS	RECALC	YES

5. After the spreadsheet recalculates, the cleanup costs may be found in row 42/column 54 through row 44/column 54 of the spreadsheet.

The lifetime financial analysis may be performed for all 105 cases generated by VENT-2.100.